Book of abstracts:

4TH INTERNATIONAL CONFERENCE ON SMART ENERGY SYSTEMS AND 4TH GENERATION DISTRICT HEATING: AALBORG, 13-14 NOVEMBER 2018

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4TH INTERNATIONAL CONFERENCE ON SMART ENERGY SYSTEMS AND 4TH GENERATION DISTRICT HEATING

BOOK OF ABSTRACTS

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4DH

AALBORG, 13-14 NOVEMBER 2018

4th International Conference on Smart Energy Systems and
4th Generation District Heating, 13-14 November 2018

Book of Abstracts

Aalborg University
Department of Planning
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Peter Kristensen and May-Britt Vestergaard Knudsen

Preface

It is a great pleasure to welcome you to the **4th International Conference on Smart Energy Systems and 4th Generation District Heating** at Aalborg University, on 13-14 November 2018.

The conference is organised by the 4DH Strategic Research Centre (4DH) and the ReInvest project in collaboration with Aalborg University. It is supported financially by Innovation Fund Denmark, The Obel Family Foundation and a series of sponsors presented on the following pages. After last year's success in Copenhagen with 150 presentations and more than 300 participants, we are indeed happy to be able to welcome you to this year's conference in Aalborg with more than 130 presentations, special workshops and H2020 project sessions as well as a panel debate. Once again, we welcome around 300 participants from 27 countries around the world. We wish to thank everyone for your valuable contributions.

The aim of the conference is to present and discuss scientific findings and industrial experiences related to the development of Smart Energy Systems and future 4th Generation District Heating Technologies and Systems (4GDH). This development is fundamental to the implementation of the European 2020 goals as well as future sustainable energy solutions in general.

The Smart Energy System approach was defined in 2011 in the CEESA project. The project addressed Danish scenarios with a particular focus on renewable energy in the transport system in a context with limited access to bioenergy. The Smart Energy System concept is essential for 100% renewable energy systems to harvest storage synergies and exploit low-value heat sources. The most effective and least-cost solutions are to be found when the electricity sector is combined with the heating and cooling sectors and/or the transport sector. Moreover, the combination of electricity and gas infrastructures may play an important role in the design of future renewable energy systems.

In future energy systems, combinations of low-temperature district heating resources and heat savings represent a promising alternative to individual heating solutions and passive or energy+ buildings. This change in the heating system also requires institutional and organisational changes that address the implementation of new technologies and enable new markets that can provide feasible solutions to society.

In its research on low-temperature district heating, 4DH enhances the understanding of supply system design, infrastructure and heat savings. All presentations, discussions, talks and debates during the conferences contribute to this understanding.

We wish you all a fruitful conference,

Henrik Lund, Brian Vad Mathiesen and Poul Alberg Østergaard
Professors at Aalborg University and Conference organisers

For reasons of copyright, the following journal papers are not included in the electronic version of Book of Abstracts:

International review of district heating and cooling (Energy 137 (2017) pp. 617-631)
Smart energy and smart energy systems (Energy 137 (2017) pp. 556-565)
The status of 4th generation district heating: Research and results (Energy 164 (2018) pp. 147-159)

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4th International Conference on

Smart Energy Systems and 4th Generation District Heating

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Call for abstracts

Important Dates 2018

15 June - Deadline for submission of abstracts for speakers (**NB** Additional upgrade to paper is optional)

14 July - Reply on acceptance of abstracts

1 September - Early registration deadline

The Smart Energy System concept is essential for 100% renewable energy systems to harvest storage synergies and exploit low value heat sources. The Smart Energy System approach was defined in 2011 in the CEESA project. The project addressed Danish scenarios with a particular focus on renewable energy in the transport system in a context with limited access to bioenergy. As opposed to, for instance, the smart grid concept, which takes a sole focus on the electricity sector, the smart energy systems approach includes the entire energy system in its identification of suitable energy infrastructure designs and operation strategies. Focusing solely on the smart electricity grid often leads to the definition of transmission lines, flexible electricity demands, and electricity storage as the primary means to dealing with the integration of fluctuating renewable sources. However, these measures are neither very effective nor cost-efficient considering the nature of wind power and similar sources. The most effective and least-cost solutions are to be found when the electricity sector is combined with the heating and cooling sectors and/or the transport sector. Moreover, the combination of electricity and gas infrastructures may play an important role in the design of future renewable energy systems. In its research on low-temperature district heating, the Strategic Research Centre for 4th Generation District Heating Technologies and Systems enhances the understanding of supply system design, infrastructure and heat savings. In future energy systems, combinations of low-temperature district heating resources and heat savings represent a promising alternative to individual heating solutions and passive or energy+ buildings. This change in the heating system also requires institutional and organisational changes that address the implementation of new technologies and enable new markets that can provide feasible solutions to society.

We invite researchers and experts from industry and businesses to contribute to further enhancing the knowledge of Smart Energy Systems and 4th Generation District Heating.

Topics

Smart Energy System analyses, tools and methodologies

Smart Energy infrastructure and storage options

Integrated energy systems and smart grids

Institutional and organizational change for Smart Energy Systems and radical technological change

Energy savings, low-temperature district heating grids and buildings

4th Generation District Heating concepts, future district heating production and systems

Planning and organization challenges for smart energy systems and district heating

Geographical Information Systems (GIS) for Energy systems, heat planning and district heating

District heating components and systems
Renewable Energy Sources and waste heat sources for district heating

Fee including materials, coffee, lunches and conference dinner:

- Normal fee: **400 EUR**
- Early registration (for presenters with accepted abstracts): **300 EUR**

4DH
4th Generation District Heating Technologies and Systems

Heat Roadmap Europe 2050

re INVEST

4th International Conference on

Smart Energy Systems and 4th Generation District Heating

13-14 November 2018 · Aalborg

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Aim and Organisers

The aim of the conference is to present and discuss scientific findings and industrial experiences related to the subject of Smart Energy Systems based on renewable energy and future 4th Generation District Heating Technologies and Systems (4GDH). It is organized by the 4DH Strategic Research Centre and the RE-INVEST project in collaboration with Aalborg University. 4DH is an international research centre which develops future 4th generation district heating technologies and systems. This development is fundamental to the implementation of Smart Energy Systems to fulfil national objectives of future low carbon strategies as well as the European 2020 goals. With lower and more flexible distribution temperatures, 4GDH can utilize renewable energy sources, while meeting the requirements of low-energy buildings and energy conservation measures in the existing building stock. RE-INVEST is an international research project which develops robust and cost-effective renewable energy investment strategies for Denmark and Europe.

Photo by Peter Kristensen

Location

The conference will take place at Nordkraft in Aalborg, and the Conference Dinner will take place at Musikkens Hus.

Submission Procedure

Both scientific and industrial contributions to the conference are most welcome. Submitted abstracts will be reviewed by a scientific and an industrial committee. Authors of approved abstracts will be invited to submit papers to special issues of

- ENERGY - The International Journal
- The International Journal of Sustainable Energy Planning and Management
- Energies (publishing requires a fee, see more in the submission form)

Best Presentation Awards will be given to a selected number of presenters at the conference.

Abstracts may be presented at the conference without uploading full paper, as this is not a requirement.

Please send your one-page abstract to 4dhConference@plan.aau.dk before 15 June 2018 including this Submission Form.

Photos by Peter Kristensen

International Scientific Committee

Prof. Dagnija Blumberga, Riga Technical University, Latvia
Dr. Robin Wiltshire, Building Research Establishment (BRE), UK
Dr. Anton Ianakiev, Nottingham Trent University
Dr. Ralf-Roman Schmidt, Austrian Institute of Technology, Austria
Dr. Hanne L. Raadal, Østfold Research, Norway
Dr. Richard van Leeuwen, Saxion University, The Netherlands
Prof. Thomas Brown, Frankfurt University, Germany
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Prof. Dr.-Ing. Ingo Weidlich HafenCity Universität, Germany
Prof. Eric Ahlgren, Chalmers University of Technology, Sweden
Prof. Sven Werner, Halmstad University, Sweden
Prof. Leif Gustavsson, Linnaeus University, Sweden
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Prof. Svend Svendsen, Technical University of Denmark
Prof. Xiliang Zhang, Tsinghua University, China
Prof. Bernd Möller, University of Flensburg, Germany
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Ass. Prof. Carsten Bojesen, Aalborg University, Denmark
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John Bøgild Hansen, Haldor Topsøe
Svante Bundgaard, Aalborg CSP

Conference Chairs

Prof. Henrik Lund, Prof. Brian Vad Mathiesen and Prof. Poul Alberg Østergaard, Aalborg University, Denmark

Further information

www.4dh.eu www.heatroadmap.eu www.reinvestproject.eu

4th International Conference on

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AALBORG UNIVERSITY
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Monday 12 November 2018 · Programme **#SES4DH2018**

4DH Technical Tour
Monday 12 November 2018 at 13:00-16:00

District Heating in Aalborg City
- On the way to becoming 100% fossil free

Aalborg is the fourth largest city in Denmark with more than 140,000 citizens and an increasing population. The district heating system consists of approximately 1,500 km pipes that supply more than 85,000 households giving a connection rate of 99% through approximately 35,000 individual meters.

This tour will introduce you to district heating in Aalborg, which is in a transition phase with the aim of becoming 100% fossil free. Aalborg Heating provides heat from three major manufacturers consisting of Nordjyllandsværket, which is a coal-fired plant, and excess heat from Aalborg Portland, a cement factory, and Reno Nord, a waste to energy plant. A pilot project is currently running in which Aalborg Heating is testing the conditions and possibilities for district cooling.

Time and venue
Pick-up and drop-off at First Hotel, Rendsburggade 5, 9000 Aalborg.
Meeting time is 12:50.

Price
35 EUR + VAT. (Refreshments included)

Registration
Please register at http://www.4dh.eu/conferences/conference-2018/registration

Deadline for registration is 10 October.
Registration is binding. Limited number of seats.

Interactive Workshop
on Heat Planning and Mapping in Europe
Monday 12 November 2018 at 13:00-16:00

H2020 programme projects Hotmaps, PLANHEAT, THERMOS and Heat Roadmap Europe offer innovative approaches for the integration of sustainable heating and cooling infrastructure at European, national, regional and local levels, thereby assisting EU Member States in the practical aspects of the implementation of Article 14 of the Energy Efficiency Directive on efficiency in heating and cooling.

Join fellow academics and researchers, industry and public sector representatives at a pre-event of the 4th Generation District Heating Conference to assess four ground-breaking tools for energy planning. In its own way, each project works to optimise thermal mapping / modelling tools to enable faster upgrade, refurbishment and expansion of existing systems, as well as tap into renewable sources and the potential of waste/excess heat.

Test each tool yourself, to discover key features of each and to see which serve the purpose of your organisation and your work. Collect and discuss details about: Geographical scope, spatial resolution, code and data requirements, mapping and other functionalities, economic and technical criteria, simulation and scenario building, IT requirements, training and implementation.

Venue
Aalborg University, Rendsburggade 14, 9000 Aalborg, Level 3, room 3.329

Registration
Please register at https://goo.gl/Zb25nG
Deadline for registration is 8 November.

4DH @4dhresearch

@HeatRoadmapEU
Heat Roadmap Europe 2050
A low-carbon heating and cooling strategy

reINVEST
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AALBORG UNIVERSITY DENMARK

Tuesday 13 November 2018 · Overall programme

#SES4DH2018

08:00-09:00 Registration and breakfast — **"KEDELHALLEN" GROUND FLOOR, LEVEL 1**

09:00-10:30 ***1st plenary session chaired by Professor Brian Vad Mathiesen***

09:00 Opening speech by Professor Brian Vad Mathiesen
09:15 Plenary keynote by Professor Henrik Lund: The Status of 4th Generation District Heating: Research and Results
09:45 Plenary keynote by Lily Riahi, advisor UNEP: District Energy in Cities: Global Perspective on Unlocking the Potential for District Heating and Cooling
10:15 Questions and discussion

PLENARY ROOM 6.1-6.3, LEVEL 6

10:30-11:00 Coffee break — **PLENARY ROOM 6.1-6.3, LEVEL 6**

Parallel sessions 1-6

11:00-12:30 ROOM 6.3 LVL 6	11:00-12:30 ROOM 6.2, LVL 6	11:00-12:30 ROOM 6.1, LVL 6	11:00-12:30 ROOM 6.8, LVL 6	11:00-12:30 ROOM 4.3.02, LVL 4	11:00-12:30 ROOM 3.3.17, LVL 3
Session 1: Smart Energy Systems	**Session 2: Future district heating production and systems**	**Session 3: Energy planning and planning tools**	**Session 4: Low-temperature district heating grids**	**Session 5: Low-temperature DH and buildings**	**Session 6: Organisation, Ownership and Institutions**
Chair: Poul Alberg Østergaard	**Chair: Neven Duic**	**Chair: Urban Persson**	**Chair: Peter Jorsal**	**Chair: Nina Detlefsen**	**Chair: Frede Hvelplund**
Session keynote: Benedetto Nastasi	**Session keynote: Richard P. van Leeuwen**	**Session keynote: Bernd Möller**	**Session keynote: Carsten Bojesen**	**Session keynote: Jan Eric Thorsen**	**Session keynote: Gijsbert Korevaar**
Hanmin Cai	Hanne Kauko	Kamal Kuriyan	Dirk Vanhoudt	Christian Holmstedt Hansen	Søren Djørup
Andrei David	Alexandre Canet	Joseph Maria Jebamalai	Igor Krupenski	Kevin Michael Smith	Niels M. Westera
Sara Bellocchi	Johannes Pelda	Jakob Zinck Thellufsen	Tobias Sommer	Pierre Vogler-Finck	Daniel Møller Sneum
Timo Kannengiesser	Marcello Aprile		Marco Pellegrini	Jens Møller Andersen	David G. Barns

12:30-13:30 Lunch — **"KEDELHALLEN" GROUND FLOOR, LEVEL 1**

12:30-13:00 Steering Committee Meeting (4DH SC members only) — **ROOM 6.8, LEVEL 6**

Parallel sessions 7-12

13:30-15:00 ROOM 6.3 LVL 6	13:30-15:00 ROOM 6.2, LVL 6	13:30-15:00 ROOM 6.1, LVL 6	13:30-15:00 ROOM 6.8, LVL 6	13:30-15:00 ROOM 4.3.02, LVL 4	13:30-15:00 ROOM 3.3.17, LVL 3
Session 7: Smart Energy Systems	**Session 8: Future district heating production and systems**	**Session 9: Energy planning and planning tools**	**Session 10: Smart Energy Systems**	**Session 11: Low-temperature DH and buildings**	**Session 12: Smart Energy Systems**
Chair: Atli Benonysson	**Chair: Gorm Bruun Andresen**	**Chair: Younes Noorollahi**	**Chair: Alfred Heller**	**Chair: Svend Svendsen**	**Chair: Bernd Möller**
Session keynote: Daniel Trier	**Session keynote: François Maréchal**	**Session keynote: Steen Schelle Jensen**	**Session keynote: Morten Hofmeister**	**Session keynote: Leif Gustavsson**	**Session keynote: Anna Volkova**
Jay Hennessy	Henrik Pieper	Matteo Giacomo Prina	Roman Geyer	Dorte Skaarup Østergaard	Nadine Aoun
Shalika Walker	Gaétan Chardon	Mostafa Fallahnejad	Olatz Terreros	Øystein Rønneseth	Kaisa Kontu
Tommy Rosén	Matteo Caramaschi	Richard Büchele	Sylvain Quoilin	Kerstin Sernhed	Sonja Salo
Nicolas Lamaison	Diego Hangartner	Julian Wruk	Wiebke Meesenburg	Anna Kallert	Morten Karstoft Rasmussen

15:00-15:30 Coffee break — **ROOMS 6.1 and 6.3, LVL 6, 3.3.17, LVL 3 and 4.3.02, LVL 4**

Parallel sessions 13-18					
15:30-16:45 ROOM 6.3, LVL 6 **Session 13: Smart Energy Systems** **Chair: Karl Sperling** **Session keynote:** **Ralf-Roman Schmidt** Salem Alsaleh Gabriele Cassetti Hironao Matsubara	**15:30-16:45 ROOM 6.2, LVL 6** **Session 14: Future district heating production and systems** **Chair: Xiliang Zhang** **Session keynote:** **Dagnija Blumberga** Jes Donneborg Borna Doračić: Marcin Bugaj	**15:30-16:45 ROOM 6.1, LVL 6** **Session 15: Low-temperature district heating grids** **Chair: John Bøgild Hansen** **Session keynote:** **Peter Jorsal** Luis Sánchez-García Aleksandr Hlebnikov Johannes Küchle	**15:30-16:45 ROOM 3.3.17, LVL 3** **Session 16: Smart Energy Systems** **Chair: Anders N. Andersen** **Session keynote:** **Elisa Guelpa** Esmir Maslesa Jonas Hinker Romain Lambert	**15:30-16:45 ROOM 4.3.02, LVL 4** **Session 17: Low-temperature district heating grids** **Chair: Carsten Bojesen** **Session keynote:** **David Pearson** Dietrich Schmidt Federico Bava Gašper Stegnar	**15:30-16:45 ROOM 6.8, LVL 6** **Session 18: Smart Energy Systems** **Chair: Sven Werner** **Session keynote:** **Bente Johnsen Rygg** Roberta Roberto Gunnar Lennermo Susana Paardekooper

16:45-17:00 Short break

17:00-17:30 Heat Roadmap Europe results: Roadmaps and the Pan-European Thermal Atlas 4 — **PLENARY ROOM 6.1-6.3, LVL 6**

17:00 Heat Roadmaps by Professor Brian Vad Mathiesen
17:15 PETA 4.3 Overview of updated information by Assistant Professor Urban Persson
17:20 PETA 4.3 Short introduction to new layers by Professor Bernd Möller

Heat Roadmap Europe 4 (HRE4) aims to develop low-carbon heating and cooling strategies, called Heat Roadmaps, by quantifying and implementing changes at the national level for 14 EU Member States. The recently finished roadmaps are presented which are in line with the long-term objective to decarbonize the energy system. They are, however, able to decarbonise heating and cooling while reducing costs. The free interactive online map, the Pan-European Thermal Atlas (Peta), gives visual and technical data on the location, and the scale of heating and cooling datasets has been updated. The latest update (Peta 4.3) is presented which incorporates innovative new features focusing on networks, costs and heat sources with new layers.

17:30-19:30 Break

19:30 Conference dinner
MUSIKKENS HUS, Musikkens Plads 1, 9000 Aalborg

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AALBORG UNIVERSITY
DENMARK

Wednesday 14 November 2018 · Overall programme (preliminary)

#SES4DH2018

08:00-09:00 Coffee — **ROOMS 6.1 and 6.3, LVL 6, 3.3.17, LVL 3 and 4.3.02, LVL 4**

Parallel sessions 19-22

9:00-10:30 ROOM 6.3, LVL 6	9:00-10:30 ROOM 6.2, LVL 6	9:00-10:30 ROOM 4.3.02, LVL 4	9:00-10:30 ROOM 6.8, LVL 6	9:00-10:30 ROOM 6.1, LVL 6
Session 19: Smart Energy Systems **Chair: Anders M. Odgaard** **Session keynote:** **Anders N. Andersen** Daniela Guericke Lennart Merkert Sara Månsson	**Session 20: Future district heating production and systems** **Chair: Louise Ödlund** **Session keynote:** **Carsten Østergaard Pedersen** Oliver Martin-Du Pan Jan van Deventer Alfred Heller Souman Rudra	**Session 21: Energy planning and planning tools** **Chair: Steen Schelle Jensen** **Session keynote:** **Casey Cole** Asad Ashfaq Russell McKenna Lisa Brange	**Session 22: Low-temperature district heating and buildings** **Chair: Jan Eric Thorsen** **Session keynote:** **Andra Blumberga** Giorgio Cucca Saleh Mohammadi Martin Crane Ahmad Said Galadanci	**ReUseHeat Session: Urban waste heat recovery - potentials and business challenges** **Chair: Alessandro Provaggi** Urban Persson Kenneth Hansen Kristina Lygnerud Chris Garside

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10:30-11:00 Coffee break — **ROOMS 6.1 and 6.3, LVL 6, 3.3.17, LVL 3 and 4.3.02, LVL 4**

Parallel sessions 23-27

11:00-12:30 ROOM 6.2, LVL 6	11:00-12:30 ROOM 4.3.02, LVL 4	11:00-12:30 ROOM 6.1, LVL 6	11:00-12:30 ROOM 3.3.17, LVL 3	11:00-12:30 ROOM 6.3, LVL 6	11:00-12:30 ROOM 6.8, LVL 6
Session 23: Smart Energy Systems **Chair: Leif Gustavsson** **Session keynote:** **Anders Dyrelund** Mario Potente Prieto Patryk Chaja Benedikt Pesendorfer P. Leoni and A. Capretti	**Session 24: Future district heating production and systems** **Chair: Peter Badstue Jensen** **Session keynote:** **Gorm Bruun Andresen** Wen Liu Maciej Widziński Muhannad Delwati Kun Zhu	**Session 25: Energy planning and planning tools** **Chair: Ralf-Roman Schmidt** **Session keynote:** **Urban Persson** Tomislav Novosel Michiel Fremouw Miguel Chang Nis Bertelsen	**Session 26: Future district heating production and systems** **Chair: Rasmus Aaen** **Session keynote:** **Louise Ödlund** Britta Kleinertz Toshihiko Nakata Cord Kaldemeyer Hrvoje Dorotić	**Session 27: Smart Energy Systems** **Chair: Benedetto Nastasi** **Session keynote:** **Vittorio Verda** Peter Lorenzen Marta Victoria Danica Maljkovic Shobhana Singh	**THERMOS National Inspire Event: User-friendly open-source software to make heat network planning easier** Steffen Nielsen Alis Daniela Torres Kamal Kuriyan Joshua Thumim

12:30-13:30 Lunch — **"KEDELHALLEN" GROUND FLOOR, LVL 1**

13:30-16:15 ***2nd plenary session chaired by Professor Henrik Lund and Professor Poul Alberg Østergaard***

13:30 Plenary keynote by Professor Mark Z. Jacobson: Transitioning towns, cities, and countries to 100% clean, renewable energy for all purposes
14:00 Plenary keynote by Professor Xiliang Zhang: District Heating in China: status quo, challenges and perspective
14:30 Plenary keynote by Professor Neven Duic: District heating and 4th generation district heating in Eastern Europe
15:00-15:45 Panel Debate: The future role of district heating and 100% renewable energy systems - introduced by Professor Sven Werner
15:45-16:15 Closing session and Award Ceremony

Coffee will be served in the room — **PLENARY ROOM 6.1-6.3, LVL 6**

4DH Technical Tour

15 November 2018, 8:30-12:00

District Heating of the Future - Brønderslev Smart Energy Concept

More than 60 % of all households in North Denmark are supplied with sustainable, flexible, decentralized district heating, thanks to an intelligent district heating system. The district heating infrastructure in the region is designed to be future-proof, and deliver a competitive and green energy solution. On this tour, you have the opportunity to experience one of the world's most efficient solar thermal plants. Brønderslev is located 30 km north of Aalborg and 30 minutes by taxi to the airport. The tour will visit Brønderslev CHP plant, which is the first CHP plant in the world to combine Concentrated Solar Power (CSP) and wood chips, while using an ORC (Organic Ranking Cycle) system to turn the energy into both electric and district heating. The plant supplies 4,600 households with heat and power, produced by 26,929 m2 CSP and a biomass plant. CSP heats a thermic oil inside a vacuum tube to 330 °C, and feds it into an ORC-engine. Oil vapour then drives the turbine and produces heat or heat/power, depending on the demand. The facility is also equipped with heat pumps, collecting the excess heat from smaller sources in the plant and feeds it into the system to further reduce loss.

Time and venue
Pick-up and drop-off at First Hotel, Rendsburggade 5, 9000 Aalborg.
Meeting time is 8:20.

Price
35 EUR + VAT. (Refreshments included)

Registration
Please register at http://www.4dh.eu/conferences/conference-2018/registration
Deadline for registration is 10 October.

Registration is binding. Limited number of seats.

Tuesday 13 November 2018 · Contents of Sessions 1-6

Session 1: Smart Energy Systems
Benedetto Nastasi: Synthetic fuels potential by Power-To-Gas integration at National level for enhancing energy independency
Hanmin Cai: Fuel shift for improving urban integrated energy system operation and efficiency
Andrei David: Techno-economic analysis of electrofuel production in a Danish Smart Energy System
Sara Bellocchi: On integrating electric vehicles into Smart Energy Systems: Italy and Germany in comparison
Timo Kannengiesser: Optimization of Urban Energy Supply Systems Considering Various Sector-Coupling Options for Different Penetration Rates of Battery Electric Vehicles

Session 2: Future district heating production and systems
Richard P. van Leeuwen: Integration of waste heat and renewables into district heating systems in East-Netherlands
Hanne Kauko: Thermal storage and optimal control for improved utilization of industrial waste heat in district heating
Alexandre Canet: Feasibility of Transporting Industrial Waste Heat Over Long Distances: A Case Study in South Wales (UK)
Johannes Pelda: Methodology to evaluate and map the potential of waste heat from sewage water by using internationally available open data
Marcello Aprile: District power-to-heat/cool complemented by sewage heat recovery

Session 3: Energy planning and planning tools
Bernd Möller: A Global Spatial Model to Identify Opportunities for Local Smart Energy Systems
Kamal Kuriyan: A combined spatial and technological model for the planning of district energy systems
Joseph Maria Jebamalai: An automated GIS-based planning and design tool for district heating: Scenarios for a Dutch city
Jakob Zinck Thellufsen: Geographical distribution of heat savings in a smart energy system

Session 4: Low-temperature district heating grids
Carsten Bojesen: Friction Reducing Additives in the Future District Heating and Cooling Systems
Dirk Vanhoudt: Technological Solutions to Reduce District Heating Network Temperatures - the TEMPO Project
Igor Krupenski: Development prospects for small low-temperature district heating networks
Tobias Sommer: Lowering the pressure in district heating and cooling networks by alternating the connection of the expansion vessel
Marco Pellegrini: Technological and non-technological barriers in the revamping of traditional district heating networks into low temperature district heating: an Italian case study

Session 5: Low-temperature district heating and buildings
Jan Eric Thorsen: Load shift experience with ULTDH booster substation for multifamily building
Christian Holmstedt Hansen: Cost efficiency of district heating for low energy buildings of the future
Kevin Michael Smith: Model predictive control of a heat-booster substation in ultra-low temperature district heating networks
Pierre Vogler-Finck: Reducing supply temperature in existing buildings with an innovative advanced heating curve control technology
Jens Møller Andersen: Lowering of return temperature in district heating systems by Integration between heating and ventilation systems in households

Session 6: Organisation, ownership and institutions
Gijstbert Korevaar: Agent-based modelling for the thermal energy transition of natural gas dependent neighborhoods
Søren Djørup: The Technical Rate of Substitution between Wind Power and Photovoltaics in a Smart Energy System
Niels M. Westera: Exploring community acceptance of ownership models for district heating as an alternative to natural gas-based residential heating in a city in the Netherlands
Daniel Møller Sneum: State of the art in the States: Applying an analytic framework for flexibility in US district energy systems
David G. Barns: The value(s) of thermal storage

Tuesday 13 November 2018 · Contents of Sessions 7-12

Session 7: Smart Energy Systems
Daniel Trier: Sector coupling and distributed energy storages for the integration of renewable energy sources
Jay Hennessy: Thermal grid flexibility: a review of district heating thermal storage to facilitate flexibility
Shalika Walker: Gas-free alternatives for existing buildings with the use of heat pumps and thermal storage – a case study
Tommy Rosén: System perspective on biogas use for transport and electricity production
Nicolas Lamaison: Storage Influence in a Combined Biomass/Power-to-Heat Production Plant

Session 8: Future district heating production and systems
François Maréchal: Towards the 5th generation of district heating/cooling systems
Henrik Pieper: Large-scale heat pump integration model: A case study of Tallinn district heating
Gaétan Chardon: Absorption heat pumps in district heating networks: 4 operating modes
Matteo Caramaschi: Novel Domestic Hot Water Microbooster Heat Pump in Ultra-Low Temperature District Heating
Diego Hangartner: Heat pumps in district heating and cooling systems – Case studies for Switzerland

Session 9: Energy planning and planning tools
Steen Schelle Jensen: Introducing SCADA for district heating distribution
Matteo G. Prina: Creating optimal transition pathways from 2015 to 2050 towards low carbon energy systems using the EnergyPLAN software: methodology and application to South Tyrol
Mostafa Fallahnejad: Impact of heating planning on the economic viability of District heating in Brasov-Romania
Richard Büchele: Integrated strategic heating and cooling planning on regional level for the case of Brasov
Julian Wruk: An optimisation model for smart distribution network planning

Session 10: Smart Energy Systems
Morten Hofmeister: Solar Thermal – innovative technology and essential energy source in smart energy systems
Roman Geyer: Barriers and Opportunities for Large-Scale Heat Pumps in Austrian District Heating and Cooling Networks
Olatz Terreros: Investigating heat pump pooling concepts in rural district heating networks in Austria
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User-friendly open-source software to make heat network planning easier

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Kamal Kuriyan: Energy system modelling concepts for district heating
Joshua Thumim: Introduction and demonstration of the THERMOS tool

AALBORG CITY CENTRE

1: Nordkraft, conference	2: Musikkens Hus, conference dinner
3: Hotel Aalborg	4: CABINN Aalborg Hotel
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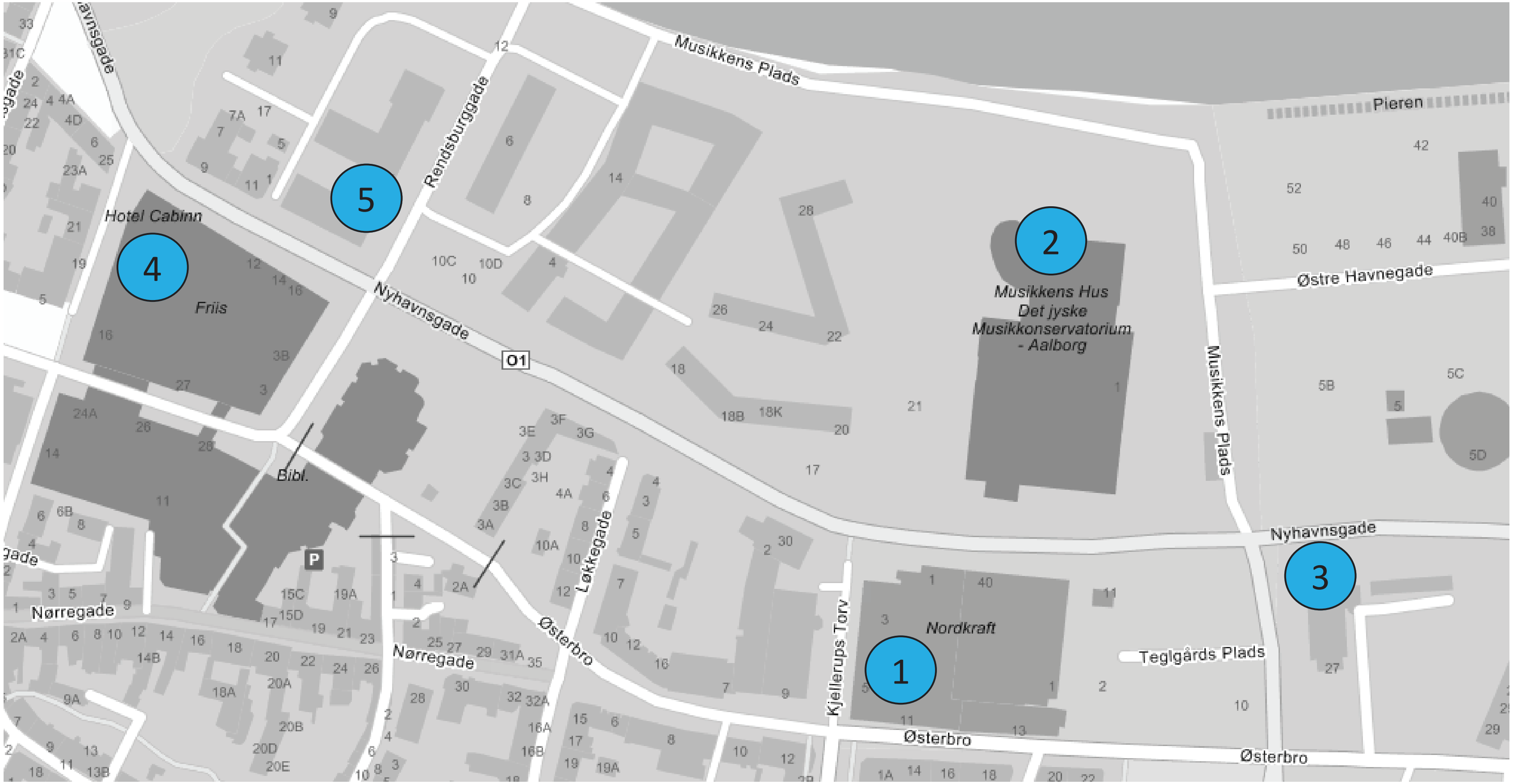


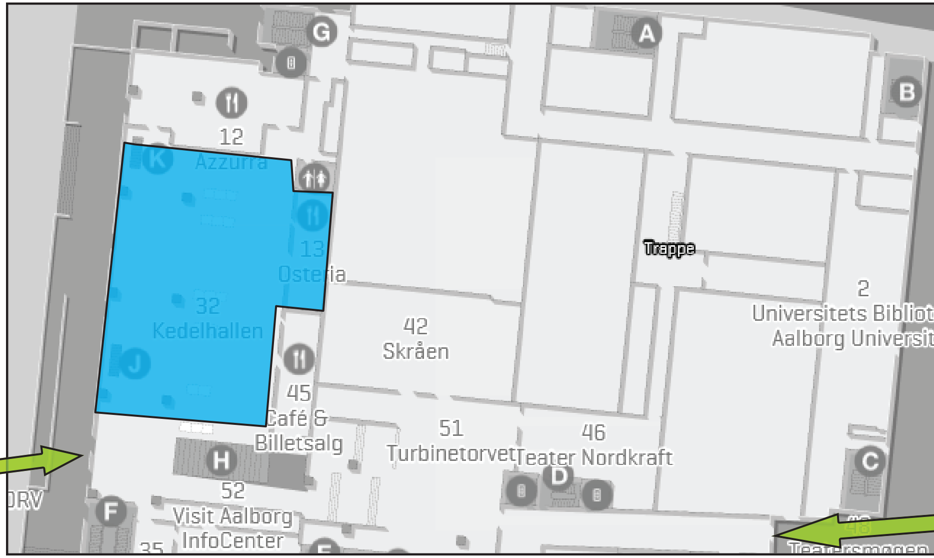
NORDKRAFT FLOOR PLAN

LEVEL 1:

REGISTRATION/ BREAKFAST/LUNCH

ENTRANCE FROM KJELLERUPS TORV

ENTRANCE FROM TEGLGAARDS PLADS



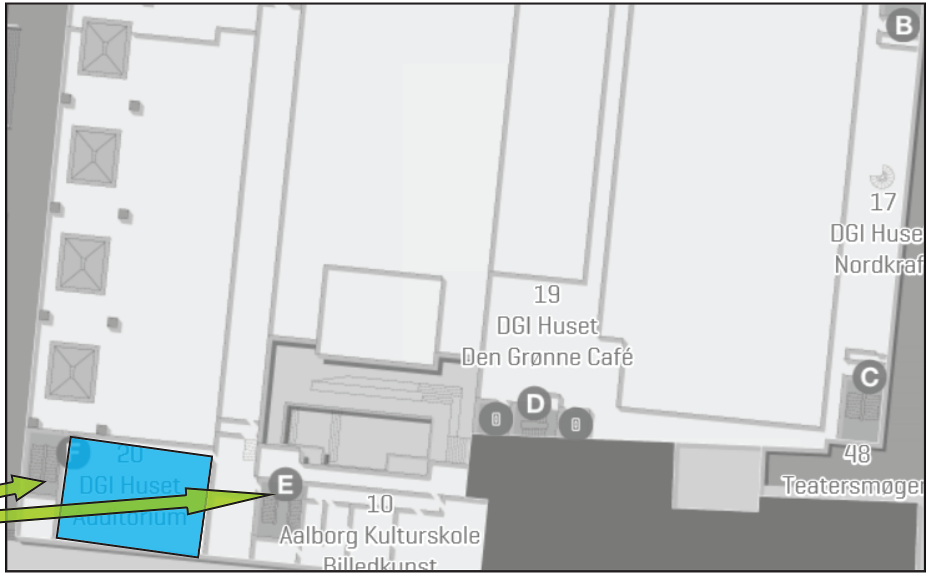
LEVEL 3:

ROOM 3.3.17

STAIRS FROM LEVEL 1

ELEVATOR/STAIRS TO LEVEL 6

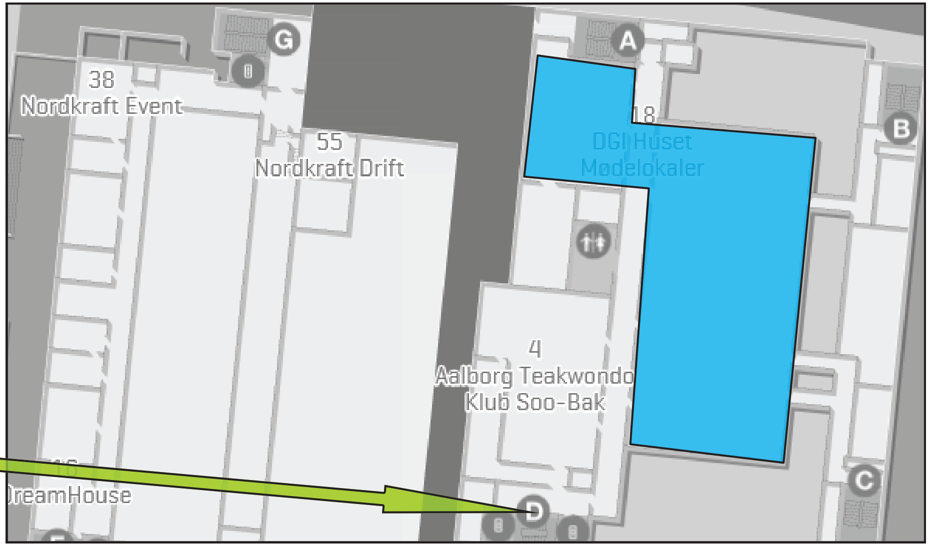
NORDKRAFT FLOOR PLAN



STAIRS FROM LEVEL 3

LEVEL 4:

ROOM 4.3.02



ELEVATOR/STAIRS FROM LEVEL 3

LEVEL 6:

ROOMS 6.1, 6.2, 6.3, 6.8

DESMI

DESMI - silver sponsor of this year's conference

DESMI provides energy efficient pump solutions both for applications in the heat production plants as well as for the transmission and distribution network.

The DESMI pump solutions are recognized as being highly energy efficient with low NSPH values. The pumps have a long life cycle and are very maintenance friendly.

The DESMI centrifugal pump range comprise of:

• NSL in-line pumps for high pressure and high capacities.
• NSLV/H – end suction pumps for high pressure and medium/high capacities.
• DSL in-line pumps for moderate pressure and even larger capacities than NSL.
• ESL in-line pumps for lower pressure and capacities.

We are able to supply flow capacities up to 5,400 m^3/h, pressure ratings up to PN25 as well as temperature solutions below 150 degr. C.

More than 500 District Heating project supplies are recorded in our archives.

DESMI has e.g. supplied for these District Heating projects:

Denmark – Aalborg District Heating Co. – Rærup Pumping Station – NSL300-415 centrifugal pumps, each with a capacity of 2,600 m^3/h.
Denmark – Vestforbrænding Copenhagen – many pump supplies over the years (e.g. NSL 250-415).
Holland – Nuon Energy Company (Vattenfall) – several pump supplies e.g. for WKC Almere Power plant.
China – Zunhua Power and Heating plant (160 km east of Beijing) - NSL300-525 pumps, each with a capacity of 1,250 m^3/h at 110 mWC and 1742 rpm.
China – Harbin Daoli District Heating Scheme – NSL & DPV pumps
Norway - Lillestrøm e.g. NSL 300-525 pumps

DESMI has also supplied pump solutions for district heating projects in many other countries, e.g. Sweden, Iceland, Poland, the Baltic Republics, Hungary, the Czech Republic, Kazakhstan, Mongolia etc.

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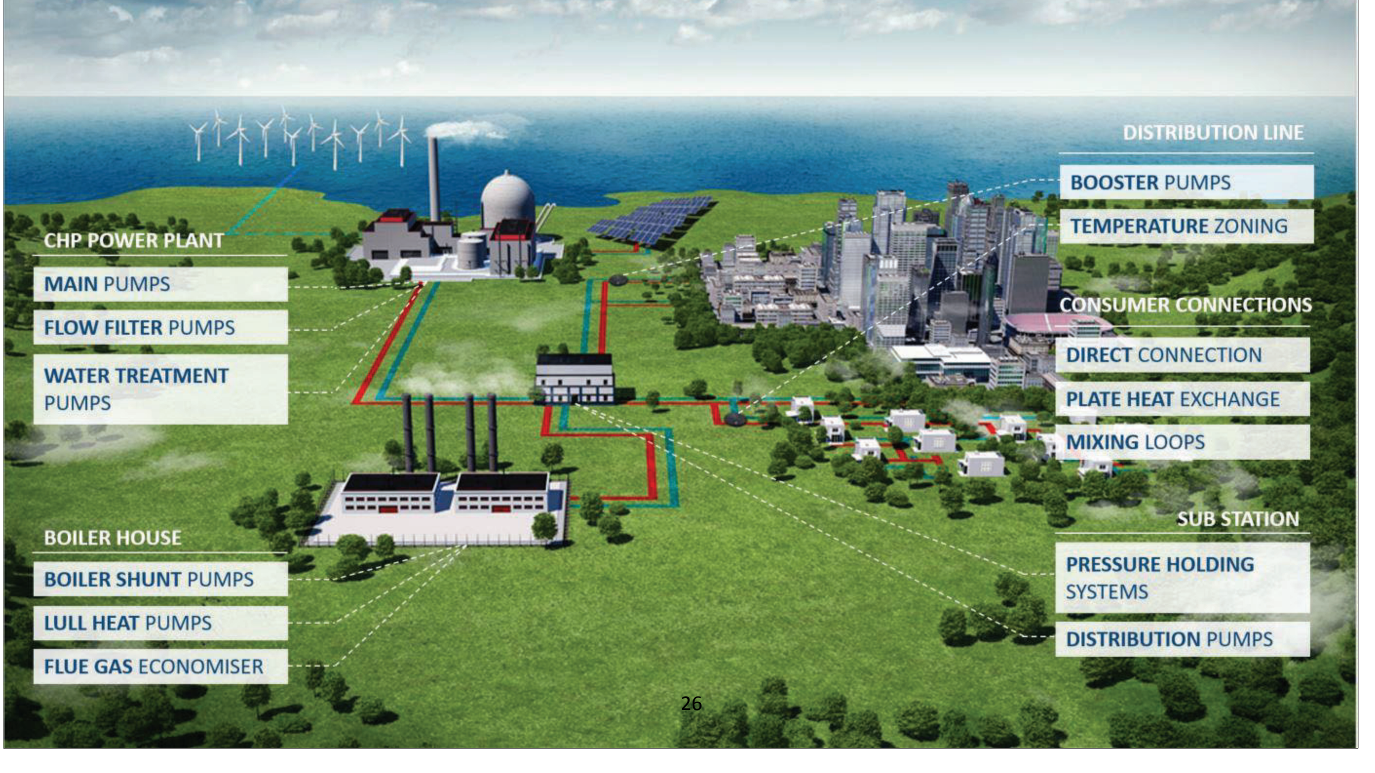
Grundfos develops, produces and sells pump solutions, which help reduce water and energy related challenges globally.

In district energy we are relentlessly ambitious in optimizing our solutions and we work with all decision makers to develop the most reliable and efficient solutions. This is proven most successful when engaged already in the design process.

Our latest focus is to help District Heating Utilities reducing their heat and pressure losses through temperature control, distributed pumping and by creating low temperature city zones with pre-fabricated mixing loops and intelligent control.

An annual production of more than 17 million pump units positions the Grundfos Group as one of the world's largest pump manufacturers. The Group employs approximately 19,000 people located in companies in 56 countries.

Grundfos was founded in 1945 and today the Poul Due Jensen Foundation is the main shareholder and profits are re-invested in the company.



LOGSTOR - silver sponsor of this year's conference

LOGSTOR is the leading supplier of pre-insulated pipe systems for energy-efficient transportation of liquids and gases for district heating and cooling, industrial purposes as well as oil and gas industry.

The initial investment in a district energy system is significant. However, it counts for the minor part of the total cost of ownership; as much as 70% is taken up by ongoing operational expenses, such as heat loss, pumping and maintenance. As a result, operators are looking for more efficient solutions that will deliver the best return on their investment.

At LOGSTOR, we help our customers to lower the total cost of ownership across the network through innovative solutions that deliver effective system designs, a simpler and more sustainable installation process and market-leading technologies that provide minimal heat loss and a lifetime of reliability and performance. We have comprehensive experience in managing the entire process of planning, design, training, installation, maintenance and all aspects of system integration.

The durability and high insulation properties of LOGSTOR's pre-insulated pipe systems make sure as much as possible of the energy generated gets to the end destination, with no leaks and with the absolute minimum of heat loss – even over long distances. This helps dramatically reducing operational costs as well as CO2 emissions.

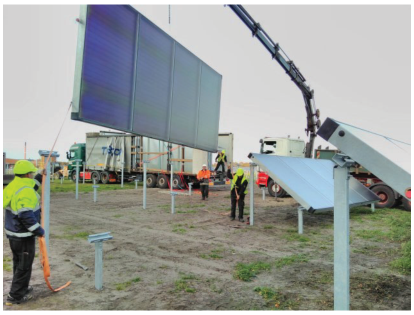
Our focus is to reduce complexity and cost at every stage by driving value and efficiency throughout the lifecycle of our customer's pipe system, with the highest and most consistent insulation values over a lifespan exceeding 30 years.

Inventing the pre-insulated pipe technology more than 50 years ago, LOGSTOR has delivered more than 200,000 km of pre-insulated pipes. Today we offer the industry's most extensive range of products and support services with a solution tailored for every need.

Headquartered in Løgstør, Denmark, LOGSTOR has subsidiaries in our main markets as well as a network of agents and sales offices. The LOGSTOR Group's seven production facilities are situated in Denmark, Poland, Sweden and Finland.

Savosolar - silver sponsor of this year's conference

Savosolar is a game changer of solar thermal energy. We provide the world's most efficient energy supply at the lowest energy cost. Our solar thermal collectors are the most efficient in the world for large scale systems.



We provide well designed and efficient solar thermal systems for the heating of buildings, industrial processes and domestic hot water. Savosolar's energy solutions are focused towards large scale applications including district heating and industrial applications.

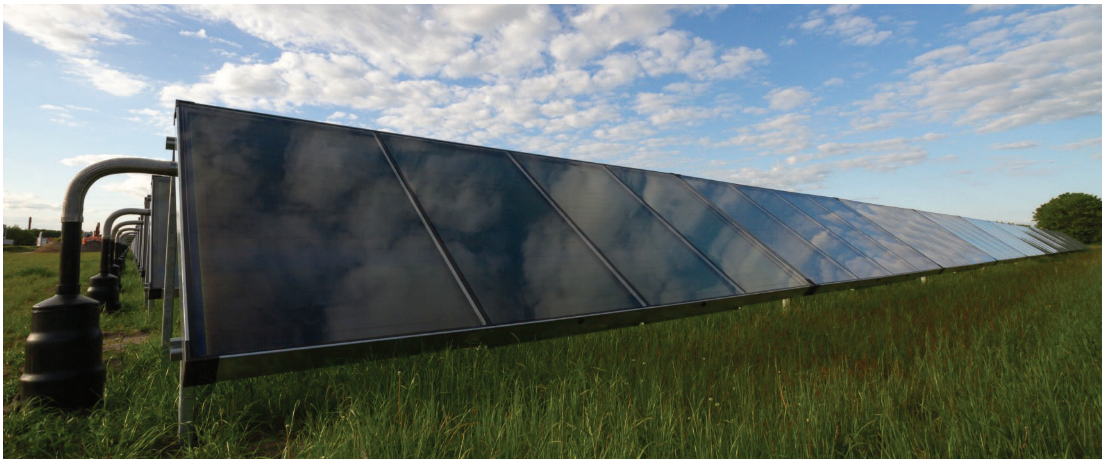
We deliver complete systems from design to installation, using the best local partners to help our customers produce competitive clean energy.

District heating is a very suitable application for solar thermal heating, especially in networks with low temperatures. Solar district heating plants increase the overall efficiency in residential and industrial areas and the higher yield provided by our collectors make them ideal for large scale applications.

Savosolar offers complete solar thermal system design and installation for district heating plants. There are several industries which use process heat and which can benefit from the use of solar thermal process heating. The higher yield provided by Savosolar's collectors make them particularly attractive for use in large and medium size installations.

Together with our local partners, we can design and deliver the entire solar system for your district heating plant or industry.

www.savosolar.com includes references (see more at savosolar.com/applications/references-map/)



Aalborg Forsyning - silver sponsor of this year's conference

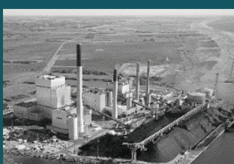
Aalborg Forsyning provides District Energy solutions for Aalborg and surroundings with very high reliability and at very cost-efficient terms. The supply includes district heating, gas and district cooling (2021) and we aim at minimizing energy consumption and to have a 100 % renewable, diversified energy system during the next decades.

Aalborg Forsyning, Energi has four main activities:

- We ***produce*** district heating, gas and electricity.
- We **sell** district heating, gas and electricity.
- We **distribute** district heating and gas to customers in Aalborg and the surrounding communities.
- We offer **services and solutions** to minimize the energy consumption for both private and public customers and industries.

From 2021 Aalborg Forsyning, Energi adds district cooling to the portfolio of products.

Aalborg **Forsyning**

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Best Senior Presentation Award is donated by Kamstrup

The presentations made by senior researchers at this year's conference on Smart Energy Systems and 4th Generation District Heating will all be competing for the Best Presentation Award sponsored by Kamstrup. Kamstrup will donate 1000 euro to the winner of the category.

At last year's conference, the winners were selected on their ability to communicate the science within their field of district heating research and thus make district heating more attractive and useful to the consumer.

Last year, Kamstrup sponsored the Best PhD Presentation Award. Kanau Takahashi from Kyoto University won the Best Presentation Award with "District heating in Japan – current situation, challenges and possibilities".

In 2017, Kanau Takahashi was happy to receive his award for Best PhD Presentation sponsored by Kamstrup. Photo: Poul Alberg Østergaard

Best PhD Presentation Award is donated by Danfoss

The PhD fellows making presentations at this year's conference on Smart Energy Systems and 4th Generation District Heating will all be competing for the Best Presentation Award sponsored by Danfoss. Danfoss will be donating the PhD Award worth 1000 euro to an aspiring researcher with excellent communication skills.

The award ceremony will take place on the second conference day at 3.45 pm in the plenary room 6.1-6.3, level 6.

Last year, Danfoss sponsored the Best Senior Presentation Award. Svend Svendsen from the Technical University of Denmark won the award for his presentation "Solutions for low temperature heating of rooms and domestic hot water in existing buildings".

In 2017. Svend Svendsen from the Technical University of Denmark won the Best Presentation Award for senior researchers sponsored by Danfoss. Photo: Poul Alberg Østergaard

CONFERENCE CHAIRS

Henrik Lund, Head of 4DH and Professor in Energy Planning at Aalborg University, Denmark

Professor Henrik Lund has headed several large research projects in Denmark and Europe. He holds a PhD in "Implementation of sustainable energy systems" (1990) and a senior doctoral degree in "Choice Awareness and Renewable Energy Systems" (2009). Henrik Lund has more than 30 years of research experience and involvement in Danish energy planning and policy making. Among others, he has been involved in the making of the Danish Society of Engineers' proposal for a future 100% Renewable Energy Plan for Denmark. He has headed several large research projects in Denmark and Europe. Henrik Lund is the main developer of the advanced energy system analysis software EnergyPLAN, which has more than 1000 registered users around the world. Henrik Lund is on the Thomson Reuter's list of highly cited researchers in the world within the topic of engineering. He has contributed to more than 300 books and articles and is Editor-in-Chief of Elsevier's international journal ENERGY.

Brian Vad Mathiesen, Deputy Head of 4DH and Professor in Energy Planning at Aalborg University, Denmark

Brian Vad Mathiesen, Professor in Energy Planning at Aalborg University, is one of the world's leading researchers in renewable energy systems. He is ranked among the top 1% researchers in the world in the Thomson Reuter's list of highly cited researchers; he is Vice-Chair of the European Commission's Horizon 2020 Advisory Group for Energy (AGE) and is a member of the European Commission's expert group on electricity inter-connection targets in the Energy Union. In his research, Brian Vad Mathiesen focuses on the technological, economic and societal shift to renewable energy, large-scale integration of fluctuating resources (e.g. wind power) and the design of 100% renewable energy systems. Brian Vad Mathiesen was one of the leading researchers behind the concepts of Smart Energy Systems and electrofuels. He has published more than 160 scientific articles and reports and is the editor and editorial board member of various international journals.

Poul Alberg Østergaard, WP leader in 4DH and Professor in Energy Planning at Aalborg University, Denmark

Poul Alberg Østergaard is Professor in Energy Planning at Aalborg University. He holds a PhD in “Integrated Resource Planning” (2000) and has more than 20 years of research and teaching experience within Energy Planning. Poul A. Østergaard’s research competences include analysis of energy systems with large-scale integration of fluctuating renewable energy sources; optimisation criteria of energy systems analyses, and sustainable energy scenarios for local areas. Poul A. Østergaard has led and been involved in many research projects all focusing on renewable energy scenarios, integration of renewable energy sources into the energy system and framework conditions for renewable energy scenarios. He has authored/co-authored more than 70 scientific papers in highly reputed publications and is the editor-in-chief of the International Journal of Sustainable Energy Planning and Management. Furthermore, Poul A. Østergaard is the Programme Coordinator and a distinguished teacher of the M.Sc. programme in Sustainable Energy Planning & Management at Aalborg University.

ABOUT 4DH

4DH is an international research centre which develops 4th generation district heating (4GDH) technologies and systems. This development is fundamental to the implementation of the European 2020 goals as well as the Danish aim of being fossil fuel-free by 2050.

In 4GDH systems, synergies are created between three areas of district heating, which also sum up the work of the 4DH Centre: grids and components; production and system integration, and planning and implementation.

4DH is based on a unique collaboration between industry, universities and the public sector to investigate the potential for and develop future district heating systems and technologies, known as 4th generation district heating (4GDH). With lower and more flexible distribution temperatures, 4GDH can utilize renewable energy sources, while meeting the requirements of low-energy buildings and energy conservation measures in the existing building stock.

4DH has created focus on and knowledge about the future 4GDH potential within the district heating industry. 4GDH systems and technologies will play a large part in a future cost-effective sustainable energy system and are likely to replace the import of fossil fuels and create jobs and economic growth in Denmark and in Europe.

Among other results of 4DH, the Heat Roadmap Europe studies have developed the most advanced knowledge about energy planning currently available for analysing the heating sector in Europe and have demonstrated how a simultaneous expansion of heat savings, district heating and heat pumps will result in the most economical low-carbon heating sector for Europe.

Read more about the 4DH Research Centre and its results at www.4dh.eu.

ABOUT RE-INVEST

RE-INVEST is a four-year research project gathering 17 partners from universities and key energy players in a unique approach to the complete redesign of the entire energy system, utilizing the synergies between heat, electricity and transport.

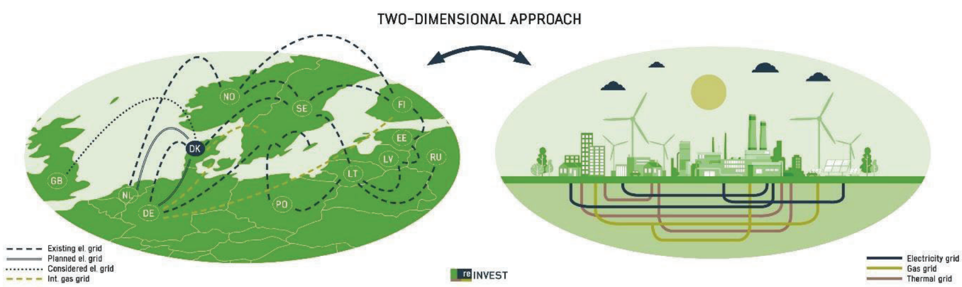
RE-INVEST aims at designing robust and cost-effective investment strategies that will facilitate an efficient transformation towards a sustainable or 100% renewable energy system in Denmark and Europe.

RE-INVEST addresses how to overcome the silo thinking that characterizes traditional energy sectors, by using a two-dimensional interconnectivity approach as well as existing and new energy infrastructures. The aims are:

1. To develop the Smart Energy System concept and identify synergies in low-cost energy storages across sectors as well as energy savings on the one side, and international electricity and gas transmission on the other side, when expanding e.g. wind power;

2. To support stakeholders within renewable energy in Denmark and Europe and enable the industrial partners in the project to be early adopters of trends in integrated energy markets, thus having cutting edge R&D for key technologies in future sustainable energy systems;

3. To share data, results, models and methodologies on open platforms and be open to new partnerships.



Read more about RE-INVEST at www.reinvestproject.eu.

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Energy Storage and Smart Energy Systems

Henrik Lund[1], Poul Alberg Østergaard[1], David Connolly[2], Iva Ridjan[2], Brian Vad Mathiesen[2], Frede Hvelplund[1], Jakob Zinck Thellufsen[1], Peter Sorknæs[1]

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ABSTRACT

It is often highlighted how the transition to renewable energy supply calls for significant electricity storage. However, one has to move beyond the electricity-only focus and take a holistic energy system view to identify optimal solutions for integrating renewable energy. In this paper, an integrated cross-sector approach is used to argue the most efficient and least-cost storage options for the entire renewable energy system concluding that the best storage solutions cannot be found through analyses focusing on the individual sub-sectors. Electricity storage is not the optimum solution to integrate large inflows of fluctuating renewable energy, since more efficient and cheaper options can be found by integrating the electricity sector with other parts of the energy system and by this creating a Smart Energy System. Nevertheless, this does not imply that electricity storage should be disregarded but that it will be needed for other purposes in the future.

Key words:

Smart energy systems
Energy Storage
Renewable energy
Heating
Transportation
URL:
dx.doi.org/10.5278/ijsepm.2016.11.2

Abbreviations

CAES	Compressed air energy storage
CHP	Cogeneration of heat and power
NaS	Natrium Sulphur (Sodium Sulphur) electricity storage
PHS	Pumped hydro storage

1. Introduction

The transition from a fossil fuel- to a renewable energy-based energy system is a change from utilising stored energy to tapping fluctuating energy sources that must be harvested when available, and either used instantaneously, or stored until the moment of use. Dealing with this basic condition of the ongoing system change, it is often highlighted how a transition into a 100% renewable energy supply or even less ambitious large-scale integration of renewable energy into the energy system calls for a new magnitude of energy storage. Especially within the electricity supply, a smart grid approach has focused on the need for electricity storage [1–3] in combination with flexible electricity demand and the expansion of transmission lines to neighbouring areas [4]. Sometimes it is even stated that renewable energy is not a viable option unless electricity can be stored [5]. Similarly, Locatelli et al. state *"Electrical Energy Storage Systems (ESS) are one of the*

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most suitable solutions to increase the flexibility and resilience of the electrical system"[6] and Tan et al. "point out smart [..energy storage systems] is a promising technology for [..micro grid] and smart grid applications" [7].

A key problem with much of the literature in relation to storage and renewable energy systems is their tendency to focus only on the generated fluctuating electricity and its direct storage from a smart grid approach. Even though the term smart grid can refer to different types of grids, it has for many years been associated exclusively with smart electricity grids, while other potential smart grid types, gas and thermal have been neglected. Electricity storage is and will be an important part of the renewable energy system puzzle but electricity's conversion to different storable and transportable energy carriers is crucial in order to transit to 100% renewable energy supply. The overall design of the energy system needs to be rethought as for the integration of flexible generation, different conversion technologies and grid solutions.

Therefore, in order to identify the best solutions one has to move beyond the simple smart grid approach and take a more holistic view as suggested by some authors [8–12]. Electricity storage [13], flexible electricity demand [14] and transmission capacity [15] have either limited integration capacity or are associated with higher costs or actual opposition as in the case with transmission grid expansion [16].

2. Scope, methodology and structure

This paper investigates the most efficient and least cost storage options as a part of a Smart Energy Systems Approach, as defined in [17]. By using this approach it is explained why the best storage solutions can be found by integrating the individual sub-sectors of the energy system. One of the main reasons why a cross-sector approach can identify more economically viable solutions is the cheaper and more efficient storage technologies that exist in the thermal and transport sectors, compared to the electricity sector.

The paper is written as a synthesis of the authors' previous research within the field, thus putting forward and integrating analyses and results into a comprehensive line of argument investigating first storage in different parts of the energy system, then size and cost of storage in the energy system followed by the role of thermal storage in smart energy systems. The discussion is broadened to the integration of cooling, transportation and biomass into the energy system, ending with findings on what can be accomplished at an energy systems level by utilising a smart energy systems approach with proper use of storage.

For optimal system configurations, all potential decision variables should be considered using some sort of heuristics [18], however this article focuses on the potential role of storage across the energy system as well as the benefits from integrating traditionally separate parts of the energy system – without locating specific optimal system configuration.

3. Electric, thermal, gas and liquid energy storage

This section looks in to electric, thermal, gas and liquid storage from an investment, efficiency and sizing perspective.

3.1 Cost and efficiency of energy storage options

There is a fundamental cost difference between storing electricity and storing other forms of energy. Here electricity storage is defined as a storage in which inputs and outputs are electricity even though typically electricity is converted to other forms of energy in the process.

Figure 1 shows the typical cost of electricity storage compared to thermal, gas and liquid fuel storage technologies. There is a variety of different technologies and sizes within each type of energy storage, which influences the investments and operation and maintenance costs. Even though the exact costs vary, the magnitude of these differences does not change significantly, with the costs indicating that thermal storage is 100 times cheaper in terms of investments per unit of storage capacity, compared to electricity storage. Moreover, gas and liquid fuel storage technologies are again substantially lower in investments than a thermal storage per unit of storage capacity. Note that the costs for these latter are based on underground natural gas caverns and oil tanks, however in a future renewable energy system this can also be methane or methanol produced from biomass and hydrogen from electrolysis or similar sorts of renewable energy-based fuels [19].

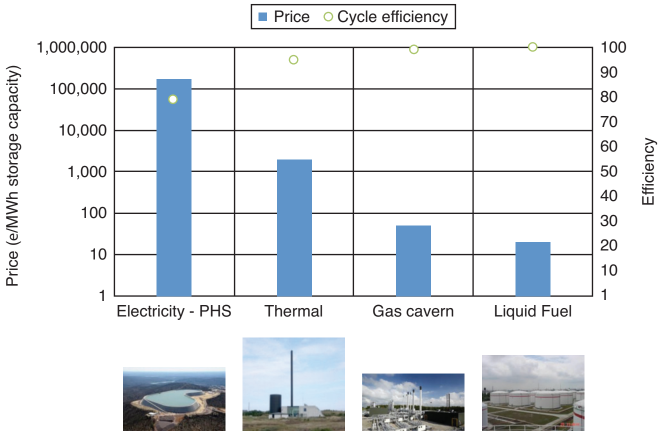

Figure 1: Investment cost and cycle efficiency comparison of electricity, thermal, gas and liquid fuel storage technologies. See assumptions, details and references in Appendix 1.

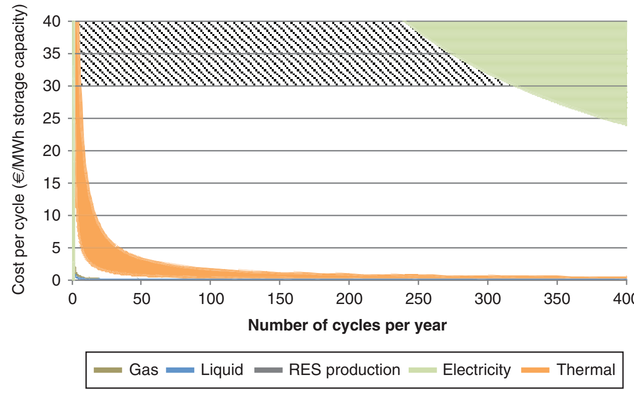

Figure 2: Annualized investment cost per use-cycle vs annual numbers of use-cycles. In the diagram the cost is also benchmarked against the cost of producing renewable energy, here shown for a wide cost span by grey (extension along horizontal axis is for presentation only; there is no cyclic dependence for renewable energy production). See assumptions, details and references in Appendix 1.

In addition to the investment issue, electricity storage is prone to significantly higher losses than any of the other types of energy storage, particularly in conversion losses. Gas caverns and oil tanks have practically nil loses; thermal storage has losses of maybe 5 percent depending heavily on size and retention time – however as electricity in almost all instances include conversion to and from the storage, losses are much more significant here.

As a consequence of investment costs and losses, the economic feasibility of electricity storage technologies depends highly on the variation in electricity prices, typically on a daily basis. However, the nature of fluctuating renewable electricity sources, such as wind power, does not typically generate such price variations. Therefore even in a system with a high share of wind power, such as the Danish case, studies show that investments in electricity storage are not feasible for the simple reason that the storage will not be used often enough to justify the relatively high initial investments [20].

Figure 2 shows how the per-use-cycle annualized investment costs of storing different forms of energy vary with the number of use cycles per year. The diagram is based on large storage technologies and shows how investment in electricity storage capacity in general requires annual cycles of at least 300-350 (equal to nearly once a day) to be able to match the cost of producing renewable energy as indicated by the hatched area. When comparing the cost of storing to the cost of producing renewable energy it should be noted that even though the electricity storage investment costs at e.g. 400 cycles per year are below the upper cost range of producing renewable energy, these storage costs include the purchasing of power to fill the storage and the operation and maintenance of the storage – nor the storage or conversion losses involved. Thus even without losses and if there is a freely available electricity source, initial investment costs in electricity storage are so high that power from the storage will only be on par with renewable electricity production if used nearly daily.

On the other hand, thermal storage investments and especially gas and liquid fuel storage are also feasible when storing energy with significantly fewer annual cycles. Here energy can be stored for weeks, months and even years due to investment costs which are even smaller. Thus, the feasibility of these other energy storage technologies is much better, especially when the energy system is rearranged to connect renewable energy to thermal, gas and/or liquid storage technologies.

Clearly, electricity storage has a more direct effect on the ability of the energy system to integrate fluctuating renewable electricity sources such as wind power [21], so a comparison cannot be made simply based on investment costs, cycle efficiencies and investment costs per cycle as shown in Figures 1 and 2. The electricity system needs to be balanced at all times but to the extent possible other storage types are more favourable as discussed as discussed later in this paper later in this paper.

3.2. Community vs individual domestic storage

Figures 3 and 4 illustrate another important factor, namely that there is a large element of economy of scale in energy storage. Figure 3 shows this point for thermal storage technologies by comparing a domestic 160 litre hot water tank with a 6000 m^3 thermal storage used by a local cogeneration of heat and power (CHP)-based district heating company [22]. Again there is a factor of 100 difference between the investments, but this time due to scale rather than type. Moreover one should note that the local CHP plant in this case has a storage capacity equal to 4 m^3 for each dwelling, whereas the maximum thermal storage installed with individual heating solutions is usually less than 1 m^3. These individual solutions are typically restricted to 1 m^3 due to the space required for the tanks. If even larger thermal storage capacity is considered, such as the seasonal thermal storage installed in recent district heating-connected solar thermal plants in Denmark[2], then the unit cost of thermal storage is reduced by an additional factor of approximately five compared to the unit cost of storage for a local CHP plant.

For the communal heat storages, this of course requires the presence of district heating systems which introduces additional heat losses in the system. In Denmark, heat losses in district heating networks vary considerably from system to system depending mainly on geographic heat demand intensity, but losses are on average approximately 20%. Efficiency improvements in the system outweigh these losses [23,24] and in the future, losses may be decreased by lowering the forward temperature of district heating grids [25].

Figure 4 illustrates how this in principle is the same for electricity storage technologies, even though the economy-of-scale influence is not as substantial as for thermal storage. In addition, for gas and liquid fuel storage technologies, there is an element of economy of scale but it is not as important since the costs of these types of energy storage are already low compared to the other costs in the energy supply. Furthermore, where charging and discharging facility costs for other types of energy storage are insignificant, these are costly for electricity storage.

The important point is that, if the renewable energy system can be designed so that it avoids electricity storage altogether and instead utilizes energy that can be stored in the form of thermal, gaseous or liquid fuels, and if this can be implemented at community level rather than in individual dwellings, then it will be more feasible to develop the storage capacity needed to integrate a high share of fluctuating electricity production such as wind, wave, and solar power.

Of course, this may come with a cost in terms of losses in energy conversion, however, these are inevitable, not only in wind or solar power integration, but in general to meet heating, cooling and transport needs in a 100% renewable energy supply [26–32]. If it is accepted that these losses are inevitable when covering heating, cooling

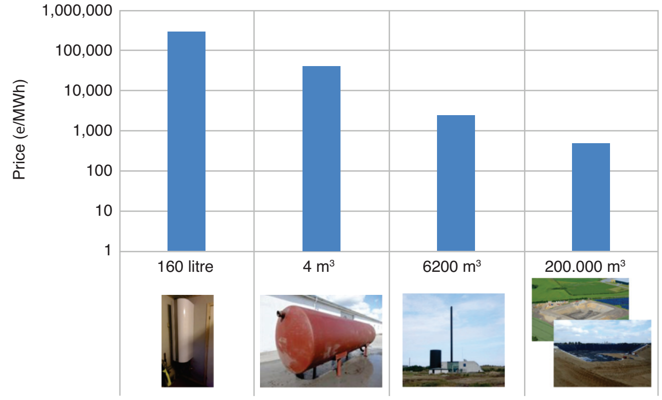

Figure 3: Investment cost comparison of different sizes of thermal energy storage technologies. The sizes correspond to storages for a dwelling, a larger building, a CHP plant and a solar DH system (see Footnote 2). See assumptions, details and references in Appendix 1.

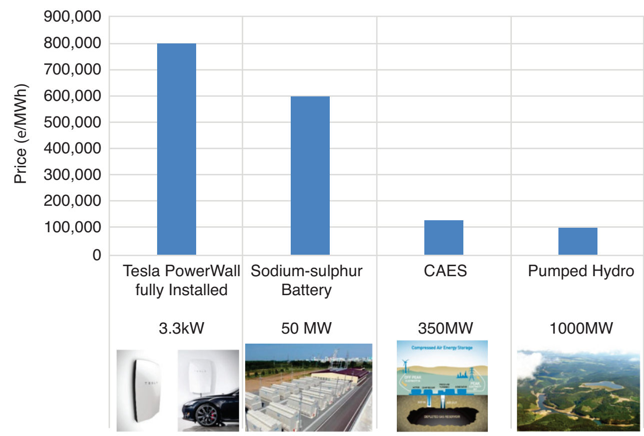

Figure 4: Investment cost comparison of different sizes of electricity energy storage technologies. See assumptions, details and references in Appendix 1.

[2] Marstal with 2306 inhabitants on the island of Ærø has two pit stores of 10,000 m^3 and 75,000 m^3 respectively [80]. Vojens (7655 inhabitants) has recently inaugurated a 203,000 m^3 pit storage [81]. Dronninglund (3328 inhabitants) has a 60,000 m^3 pit storage[82]. All population sizes from 2014 according to [83].

and transportation demands with wind and solar power, then the losses are not occurring due to the storage of the energy, but due to the conversion of energy from electricity to heat, cooling or transportation. However, in order to identify the best and the least-cost solutions, a holistic smart energy systems approach has to be adopted.

4. Smart energy systems

Smart Energy Systems may be defined as *"an approach in which smart electricity, thermal and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system"* [17]. Such systems encompass new technologies and infrastructures, which create new forms of flexibility, primarily in the conversion stage of the energy system. The flexibility is achieved by transforming from a simple linear approach in today's energy systems (i.e. fuel to conversion to end-use), to a more interconnected approach as shown in Figures 5 and 6. In simple terms, this means combining the electricity, thermal, and transport sectors so that the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar.

Heat pumps in the system provides a key conversion technology between electricity and the heating sector [33–35], which combined with heat storage and the thermal mass of buildings provides flexibility for the integration of fluctuating RES-based electricity sources. Similarly, electric vehicles provides the possibility of not only a dispatchable demand but also actual electricity storage that may be fed back to the grid [36,37]. Electrofuels create a link between the electric system and transportation, so intermittent electricity production can be connected to large-scale fuel storage. Additionally, the production cycle generates heat for the heating sector thus integrating across three traditionally separate sectors.

Note that Figure 6 does not fully portray the complexity of smart energy systems to the fullest extent possible as the smart energy system is about integrating all sectors of the energy system and exploiting synergies across these.

The following sections probe further into heating, cooling and transportation, and options for adding flexibility to the smart energy system.

4.1. Smart heating and cooling

Although it is widely accepted that the heat demand will be reduced in the future, the steps of going all the way to eliminating the need for space heating is both technically challenging and very costly, especially as the heat demand nears zero. Therefore an essential question in the design of holistic least-cost solutions in the heating sector is to identify to which extent energy should be saved and to which extent renewable energy should be supplied as well as to which extent individual solutions should be used and to which extent communal systems like district heating should be used. In this context, not only do heat savings need to be implemented in the future, it is also important to consider how the heat supply should be provided for buildings.

Many recent research and demonstration projects have also focused on the concept of a zero energy buildings [38,39], however in order to reach these objectives one

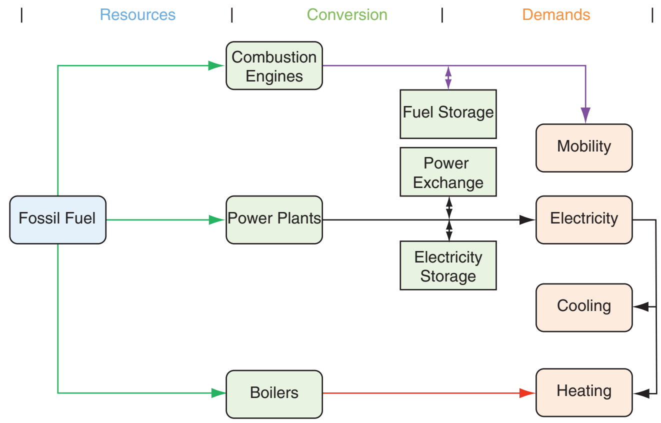

Figure 5: Today's energy systems characterised by linear paths from fuel to energy demands

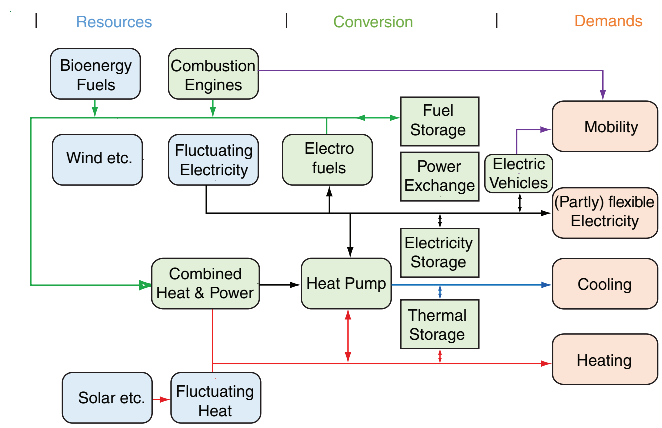

Figure 6: The integrated smart energy systems

has to include building-integrated energy supply, typically solar thermal and photo voltaic. The best solution will not be found if one considers these supplies as a part of the building; the least-cost design can only be found from a holistic smart energy approach [40].

The integration of the heating and cooling sector with electricity enables a higher fuel efficiency and increasing the share of fluctuating resources resulting in more efficient system and least-cost solutions. This becomes of even higher importance as the share of fluctuating electricity is increased towards 100% renewable energy systems.

Studies for several individual countries in Europe [41] as well as the study Heat Roadmap Europe [23,42] at the European Union level, have reached the conclusion that the least-cost way to supply heating is to combine heat savings with district heating in urban areas and individual heat pumps in rural areas. These studies also indicate that an optimal solution is to be found if savings are implemented to the level of decreasing current average heating demands by approximately 50%, although the exact number differs a bit from country to country.

The reason for applying district heating in the urban areas is that it enables obtaining the benefits of using waste heat from electricity production (CHP) and industrial waste heat [43]. Studies show that in the current system in Europe, the waste heat from electricity generation and industry is almost the same as the total heat demand of Europe [23]. As a result, by using district heating, Europe could replace half of its heating demand with waste heat and thereby save a similar share of the natural gas and oil which is currently consumed in domestic boilers.

In the future as more and more wind and similar sources replace fossil-fuel based electricity production, parts of the waste heat will come from other sources such as industry, biomass conversion and electrolysis. Moreover some heat will come from waste incineration, geothermal and large-scale solar thermal plants. However studies illustrate how the integration of wind and other fluctuating renewable electricity sources using large-scale heat pumps and thermal storage will play an important role [35,44].

The important conclusion is that power-to-heat will form an important part of the heating sector in a future renewable energy system. This applies to individual heat pumps in houses outside urban areas as well as heat pumps in district heating networks in urban areas. Similar conclusions have been made with regard to cooling [45].

One might say, that power-to-heat technology combined with dedicated heat storage or the thermal mass of buildings provide a virtual electricity storage; it can be charged when there is a high availability of renewable electricity and while it cannot be discharged back onto the grid, loads can be deferred when there is a low availability of renewable electricity.

This means that to a large extent there is the option to store renewable electricity as thermal energy at a low cost rather than at a relatively high cost in dedicated electricity storage. It will not involve any further conversion losses other than the inevitable ones that have to be accepted in any case to provide for our heating and cooling needs in the least-cost way. Furthermore, this also provides the option of increasing the integration of renewable electricity such as wind by investing in additional heat pump capacity - or to some extent also in less efficient but cheaper electric boiler capacity.

4.2. Smart biomass and transportation

In order to satisfy our transport needs in a future 100% renewable energy system with restricted biomass resources due to their high demand for various purposes [46–48], different power-to- transport options will play an important role [49,50]. In fact, electrification of the transport sector will form one of the most viable ways of ensuring balance between production and demand in the electricity system [51]. However not all transport demands can be satisfied by direct use of electricity and parts of the sector such as long-distance transportation, marine and aviation will continue to rely on gaseous and/or liquid fuel that will have be produced from available renewable energy resources. In order to solve this challenge creating an additional link between the electricity sector and transport is needed. Electrofuels [52] can store electricity in the form of liquid or gaseous fuels and hereby create flexibility in the system while meeting the demands of heavy-duty transport. In the process, fluctuating electricity is converted into hydrogen by the use of electrolysis and subsequently the hydrogen reacts with a carbon source from biomass (biogas or synthetic gas) or even from CO_2 emissions [53] to produce methane, methanol or other preferable fuels.

This enables renewable electricity storage as a gas or liquid fuel, which represents a relatively low-cost option in comparison to complex electricity storage and at the same time it provides the option of increasing the integration of wind or other fluctuating resources by investing in additional electrolysis capacity [19]. As with heating, the intention is not to supply back to the grid, but to create a deferrable load, and the conversion losses are inevitable as the energy demands for transportation needs to be meet using renewable energy sources either way.

Nastasi and Basso go as far as stating *"The Power-To-Gas option by Renewable Hydrogen production could solve the dispatch issues related to a wide deployment of RES storage devices and their priority on the energy market"*[54]

4.3. The overall system

Studies of complete regional, national or European energy transitions following the principles of a smart energy systems approach have demonstrated that it is possible to design 100% renewable energy systems where production and demand of renewable energy is balanced not only on a yearly basis but also on an hourly basis [28,30,55]. Such high-temporal resolution energy systems analyses have been conducted using the EnergyPLAN model [56,57] taking into account all types of energy (electricity, heating, cooling, electrofuels and other renewable energy fuels), conversion technologies between the sectors and hourly balance has been established using thermal, gaseous and liquid fuel storage.

A smart energy systems approach is also required to ensure the economic viability of future renewable energy-based energy systems. As noted in [58], wind power has the tendency to drive down spot market prices of electricity, thus undermining the very feasibility of wind power. Photo voltaics have the same effect, though the current implementation is not comparable to that of wind power in Denmark yet. A smart energy system with many deferrable loads across heating, cooling and transportation will thus increase the value of fluctuating renewable power generation.

5. Conclusion

The issue of energy storage is essential when discussing how to implement the large-scale integration of renewable energy both into the current system and in a future transition to a 100% renewable energy supply. A sub-sector electricity-only focus - as has been seen from a smart grid approach - typically leads to proposals primarily focused on electricity storage technologies in combination with flexible electricity demands and transmission lines to neighbouring countries. However, this paper argues that this will lead to the most expensive form of energy storage, electricity storage, which is approximately 100 times more expensive than thermal storage and even more expensive than storage for gases and liquids. It is therefore a cheaper and also a more efficient solution to utilise thermal and fuel storage technologies to integrate more fluctuating renewable energy, such as wind and solar power, than to rely on electricity storage. This however, requires a strong integration across traditionally separate energy sectors.

Thus, this paper has indicated how this cross-sector smart energy systems approach can lead to the identification of better and much cheaper options in terms of thermal, gas and liquid fuel storage in combination with cross-sector energy conversion technologies. Heat pumps, which can be in each building in the rural areas or in district heating system in the urban areas, can connect the electricity sector to thermal storage, while electric vehicles and electrofuels can connect the electricity sector to storage in the transport sector. Using these more efficient and cheaper options, it is unlikely that the other options in the electricity sector will be required solely for the integration of renewable energy. In fact, studies show that large electricity storage capacity is not economically viable for this sole purpose within any of the steps between now and a future 100% renewable energy supply.

In conclusion, for the large-scale integration of fluctuating renewable electricity sources, electricity storage should be avoided to the extent possibleis and other storage types provide an option for system balancing and flexibility while having lower costs. Direct electricity storage may be needed for other reasons but should not be prioritized if the aim is to put the electricity back to the grid.

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References

[1] Agnew S, Dargusch P. Effect of residential solar and storage on centralized electricity supply systems. Nat Clim Chang 2015;5:315–8. http://dx.doi.org/10.1038/nclimate2523.

[2] Armand M, Tarascon J-M. Building better batteries. Nature 2008;451:652–7. http://dx.doi.org/10.1038/451652a.

[3] Crabtree G. Perspective: The energy-storage revolution. Nature 2015;526:S92. http://dx.doi.org/10.1038/526S92a.

[4] Edmunds RK, Cockerill TT, Foxon TJ, Ingham DB, Pourkashanian M. Technical benefits of energy storage and electricity interconnections in future British power systems. Energy 2014;70:577–87. http://dx.doi.org/10.1016/j.energy.2014.04.041.

[5] Lindley D. Smart grids: The energy storage problem. Nat News 2010;463:18–20. http://dx.doi.org/10.1038/463018a.

[6] Locatelli G, Invernizzi DC, Mancini M. Investment and risk appraisal in energy storage systems: A real options approach. Energy 2016;104:114–31. http://dx.doi.org/10.1016/j.energy.2016.03.098.

[7] Tan X, Li Q, Wang H. Advances and trends of energy storage technology in Microgrid. Int J Electr Power Energy Syst 2013;44:179–91. http://dx.doi.org/10.1016/j.ijepes.2012.07.015.

[8] Orecchini F, Santiangeli A. Beyond smart grids – The need of intelligent energy networks for a higher global efficiency through energy vectors integration. Int J Hydrogen Energy 2011;36:8126–33. http://dx.doi.org/10.1016/j.ijhydene.2011.01.160.

[9] Orecchini F, Naso V. Energy Systems in the Era of Energy Vectors: A key to define, analyze and design energy systems beyond fossil fuels. vol. 23. London: Springer London; 2012. http://dx.doi.org/10.1007/978-0-85729-244-5.

[10] Lund PD, Mikkola J, Ypyä J. Smart energy system design for large clean power schemes in urban areas. J Clean Prod 2014; 103:437–45. http://dx.doi.org/10.1016/j.jclepro. 2014.06.005.

[11] Lund H. Renewable energy strategies for sustainable development. Energy 2007;32:912–9. http://dx.doi.org/10.1016/j.energy.2006.10.017

[12] Elliott D. A balancing act for renewables. Nat Energy 2016;1:15003. http://dx.doi.org/10.1038/nenergy.2015.3.

[13] Bourzac K. Batteries: 4 big questions. Nature 2015;526:S105. http://dx.doi.org/10.1038/526S105a.

[14] Kwon PS, Østergaard P. Assessment and evaluation of flexible demand in a Danish future energy scenario. Appl Energy 2014;134:309–20. http://dx.doi.org/10.1016/j.apenergy.2014.08.044.

[15] Blarke MB, Jenkins BM. SuperGrid or SmartGrid: Competing strategies for large-scale integration of intermittent renewables? Energy Policy 2013;58:381–90. http://dx.doi.org/ 10.1016/j.enpol.2013.03.039.

[16] Menges R, Beyer G. Underground cables versus overhead lines: Do cables increase social acceptance of grid development? Results of a Contingent Valuation survey in Germany. Int J Sustain Energy Plan Manage 2014;3:33–48. http://dx.doi.org/10.5278/ijsepm.2014.3.4.

[17] Lund H. Renewable Energy Systems - A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions. 2nd ed. Academic Press; 2014.

[18] Mahbub MS, Cozzini M, Østergaard PA, Alberti F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Appl Energy 2016;164:140–51. http://dx.doi.org/10.1016/j.apenergy.2015.11.042.

[19] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. http://dx.doi.org/10.1016/j.apenergy.2015.01.075.

[20] Lund H, Salgi G. The role of compressed air energy storage (CAES) in future sustainable energy systems. Energy Convers Manag 2009;50:1172–9. http://dx.doi.org/10.1016/j.enconman.2009.01.032

[21] Østergaard PA. Comparing electricity, heat and biogas storages' impacts on renewable energy integration. Energy 2012; 37:255–62. http://dx.doi.org/10.1016/j.energy.2011. 11.039.

[22] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems -A market operation based approach and understanding. Energy 2012;42:96–102. http://dx.doi.org/10.1016/j.energy.2012.04.003.

[23] Connolly D, Lund H, Mathiesen B V., Werner S, Möller B, Persson U, et al. Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. http://dx.doi.org/10.1016/j.enpol.2013.10.035.

[24] Hansen K, Connolly D, Lund H, Drysdale D, Thellufsen JZ. Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat. Energy 2016. http://dx.doi.org/10.1016/j.energy.2016.06.033.

[25] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating. Appl Energy 2016. http://dx.doi.org/10.1016/j.apenergy.2016.02.144.

[26] Alberg Østergaard P, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 2010;35:4892–901. http://dx.doi.org/10.1016/ j.energy.2010.08.041.

[27] Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Appl Energy 2011;88:479–87. http://dx.doi.org/10.1016/j.apenergy.2010.03.018.

[28] Kwon PS, Østergaard PA. Comparison of future energy scenarios for Denmark: IDA 2050, CEESA (Coherent Energy and Environmental System Analysis), and Climate Commission 2050. Energy 2012;46:275–82. http://dx.doi.org/10.1016/j.energy.2012.08.022.

[29] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. http://dx.doi.org/10.1016/j.rser 2016.02.025.

[30] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manage 2014;1:7–28. http://dx.doi.org/10.5278/ijsepm.2014.1.2.

[31] Lund H, Østergaard PA. Sustainable Towns: The Case of Frederikshavn – 100% Renewable Energy. In: Clark WW, editor. Sustain. Communities, New York, USA: Springer New York; 2010, p. 155–68. http://dx.doi.org/10.1007/978-1-4419-0219-1_11.

[32] Østergaard PA, Lund H. Climate Change Mitigation from a Bottom-up Community Approach. In: Clark WW, editor. Sustain. Communities Des. Handb., Amsterdam: Elsevier Butterworth-Heinemann; 2010, p. 247–65. http://dx.doi.org/10.1016/B978-1-85617-804-4.00014-8.

[33] Hedegaard K, Münster M. Influence of individual heat pumps on wind power integration – Energy system investments and operation. Energy Convers Manag 2013;75:673–84. http://dx.doi.org/10.1016/j.enconman.2013.08.015.

[34] Hedegaard K, Balyk O. Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks. Energy 2013;63:356–65. http://dx.doi.org/10.1016/j.energy.2013.09.061.

[35] Østergaard PA. Wind power integration in Aalborg Municipality using compression heat pumps and geothermal absorption heat pumps. Energy 2013;49:502–8. http://dx.doi.org/10.1016/j.energy.2012.11.030.

[36] Prebeg P, Gasparovic G, Krajacic G, Duic N. Long-term energy planning of Croatian power system using multi-objective optimization with focus on renewable energy and integration of electric vehicles. Appl Energy 2016. http://dx.doi.org/10.1016/j.apenergy.2016.03.086.

[37] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy 2008;36:3578–87 http://dx.doi.org/10.1016/j.enpol.2008.06. 007.

[38] Marszal AJ, Heiselberg P, Lund Jensen R, Nørgaard J. On-site or off-site renewable energy supply options? Life cycle cost analysis of a Net Zero Energy Building in Denmark. Renew Energy 2012;44:154–65. http://dx.doi.org/10.1016/j.renene.2012.01.079.

[39] Marszal AJ, Heiselberg P, Bourrelle JS, Musall E, Voss K, Sartori I, et al. Zero Energy Building – A review of definitions and calculation methodologies. Energy Build 2011;43:971–9. http://dx.doi.org/10.1016/j.enbuild. 2010. 12.022.

[40] Lund H, Marszal a., Heiselberg P. Zero energy buildings and mismatch compensation factors. Energy Build 2011;43:1646–54. http://dx.doi.org/10.1016/j.enbuild.2011.03. 006.

[41] Lund H, Thellufsen JZ, Aggerholm S, Wichtten KB, Nielsen S, Mathiesen BV, et al. Heat Saving Strategies in Sustainable Smart Energy Systems. Int J Sustain Energy Plan Manage 2014;4:3–16. http://dx.doi.org/10.5278/ijsepm.2014.4.2.

[42] Persson U, Möller B, Werner S. Heat Roadmap Europe: Identifying strategic heat synergy regions. Energy Policy 2014;74:663–81. http://dx.doi.org/10.1016/j.enpol.2014.07. 015.

[43] Chittum A, Østergaard PA. How Danish communal heat planning empowers municipalities and benefits individual consumers. Energy Policy 2014;74:465–74. http://dx.doi.org/10.1016/j.enpol.2014.08.001.

[44] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. http://dx.doi.org/10.1016/j.energy.2014.02.089.

[45] Rezaie B, Rosen MA. District heating and cooling: Review of technology and potential enhancements. Appl Energy 2012;93:2–10. http://dx.doi.org/10.1016/j.apenergy.2011.04.020.

[46] Lund H, Mathiesen BV, Hvelplund FK, Østergaard PA, Christensen P, Connolly D, et al. Coherent Energy and Environmental System Analysis. Aalborg: 2011.

[47] Kwon PS, Østergaard PA. Priority order in using biomass resources – Energy systems analyses of future scenarios for Denmark. Energy 2013;63:86–94. http://dx.doi.org/10.1016/j.energy.2013.10.005.

[48] Mathiesen BV, Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. Energy 2012;48:160–8. http://dx.doi.org/10.1016/j.energy.2012.07.063.

[49] Connolly D, Mathiesen BV, Ridjan I. A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system. Energy 2014;73:110–25. http://dx.doi.org/10.1016 /j.energy.2014.05. 104.

[50] Ridjan I, Mathiesen BV, Connolly D, DuiC N. The feasibility of synthetic fuels in renewable energy systems. Energy 2013;57:76–84. http://dx.doi.org/10.1016/j.energy2013.01.046.

[51] Juul N, Meibom P. Optimal configuration of an integrated power and transport system. Energy 2011;36:3523–30. http://dx.doi.org/10.1016/j.energy.2011.03.058.

[52] Ridjan I. Integrated electrofuel and renewable energy systems 2015:136. http://vbn.aau.dk/files/222785116/Ridjan_Integrated_electrofuels_and_renewable_energy_systems_PhD_2015.pdf.

[53] Lim X. How to make the most of carbon dioxide. Nature 2015;526:628–30. http://dx.doi.org/10.1038/526628a.

[54] Nastasi B, Lo Basso G. Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. Energy 2016;110:5–22.http://dx.doi.org/10.1016/j.energy.2016.03.097.

[55] Lund H, Mathiesen B V. Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050. Energy 2009;34:524–31. http://dx.doi.org/10.1016/j.energy.2008.04.003.

[56] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33. http://dx.doi.org/10.1016/j.apenergy.2015.05.086.

[57] Lund H, Münster E. Management of surplus electricity-production from a fluctuating renewable-energy source. Appl Energy 2003;76:65–74. http://dx.doi.org/10.1016/S0306-2619(03)00048-5.

[58] Lund H, Hvelplund F, Østergaard PA, Möller B, Mathiesen BV, Karnøe P, et al. System and market integration of wind power in Denmark. Energy Strateg Rev 2013;1:143–56. http://dx.doi.org/10.1016/j.esr.2012.12.003.

[59] Adolfo Gonzalez A, Ó Gallachóir B, McKeogh E, Lynch K. Study of Electricity Storage Technologies and Their Potential to Address Wind Energy Intermittency in Ireland. Cork, Ireland: 2004.

[60] Electric Power Research Institute. Electricity Energy Storage Technology Options - A White Paper Primer on Applications, Costs, and Benefits. 2010:170. http://www.epri.com/ abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001020676.

[61] Hanley S. SolarCity & Tesla Battery Create Turnkey Systems (In Depth). Www.solarlove.org 2015.

[62] Dyrelund A. Rambøll (Personal communication) n.d.

[63] Anonymous (Skagen Kraftvarmeværk. Storage tank bid n.d.

[64] Anonymous (Vaarst Vestervang Community). Bids on heat storage n.d.

[65] Anonymous (Federal Energy Regulatory Commission). Current state of and issues concerning Underground Natural Gas Storage. 2004.

[66] Dahl K. Oiltanking Copenhagen (Personal Communication) 2013.

[67] Connolly D, Lund H, Finn P, Mathiesen BV, Leahy M. Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage. Energy Policy 2011;39:4189–96. http://dx.doi.org/10.1016/j.enpol.2011.04. 032.

[68] Goldisthal Pumped Storage Station G. No Title n.d. Www.store-project.eu.

[69] OANDA. Average Exchange Rates | OANDA 2016. https://www.oanda.com/currency/average.

[70] Buß K, Wrobel P, Doetsch C. Global distribution of grid-connected electrical energy storage systems. Int J Sustain Energy Plan Manage 2016;9:31–56. http://dx.doi.org/10.5278/ijsepm.2016.9.4.

[71] Danish Energy Agency. Technology data for energy plants - Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion. Copenhagen, Denmark: Danish Energy Agency; 2015.

[72] Akhil A, Huff G, Currier A, Kaun B, Rastler D, Chen SB, et al. DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA. Albuquerque: 2013.

[73] Andresen GB, Rodriguez RA, Becker S, Greiner M. The potential for arbitrage of wind and solar surplus power in Denmark. Energy 2014;76:49–58. http://dx.doi.org/10.1016/j.energy.2014.03.033.

[74] Bang C, Vitina A, Gregg JS, Lindboe HH. Analysis of biomass prices - Future Danish prices for straw, wood and wood pellets - Final report. Ea Energy Anal 2013. https://ens.dk/sites/ens.dk/files/Analyser/analysis_of_biomass_prices_2013.06.18_-_final_report.pdf (accessed September 30, 2016).

[75] Trading Economics. Trading Economics - Coal 2009-2016 2016. http://www.tradingeconomics.com/commodity/coal (accessed September 30, 2016).

[76] Dansk Industri. Statistikoverblik - Virksomhedernes energiomkostninger 2016.

[77] Danish Energy Agency. Technology data for energy plants. 2012. http://dx.doi.org/ISBN: 978-87-7844-940-5.

[78] Energinet.dk, Danish Energy Authority. Technology Data for Energy Plants 2016. https://ens.dk/sites/ens.dk/files/Analyser/update_-_technology_data_catalogue_for_energy_plants_-_aug_2016.pdf (accessed September 29, 2016).

[79] Energinet.dk, Danish Energy Authority. Technology Data - Electricity Generation - Non-Thermal Processes 2016. https://ens.dk/en/our-services/projections-and-models/technology-data.

[80] PlanEnergi. Summary technical description of the SUNSTORE 4 plant in Marstal 2013:7. http://www.solarmarstal.dk/ media/2854117/summary-technical-description-marstal.pdf.

[81] Epp B. Denmark: 37 MW Field with 203,000 m3 Storage Underway | Solar Thermal World. Sol Therm World 2014. http://www.solarthermalworld.org/content/denmark-37-mw-field-203000-m3-storage-underway.

[82] Dronninglund Fjernvarme, PlanEnergi, Niras. Dronninglund Solar thermal plant 2014:1–12. http://www.planenergi.dk /wp-content/uploads/2015/04/Brochure_Dronninglund_2015_booklet_ENG_web_.pdf (accessed August 30, 2016).

[83] Statistics Denmark. StatBank Denmark 2016. http://www.statistikbanken.dk/statbank5a/SelectVarVal/Define.asp?MainTable=BEF44&TabStrip=Select&PLanguage=1&FF=20.

Appendix 1: Assumptions for Figures

All data shown in Figures 1-4 are shown in Tables 1 and 2 below along with references for the data. Columns 3-6 in Table 1 are only relevant for Figure 2 and the technologies included there.

Comment on annual costs

All annual costs are calculated as an annuity of the investment based on a discount rate of 3 percent per year and the given lifetime plus fixed annual operation and maintenance (O&M) costs.

Comments on electrical storage

NaS storage is based on a ratio between installed discharge capacity and storage capacity of 6h in line with [60, 67].

Compressed Air Energy Storage (CAES) is based on a 360 MW / 1478 MWh plant.

PHS costs vary considerably from site to site. A German plant is priced at about 100,000 €/MWh [68], Electric Power research Institute lists a range from 4,40,000 to 6,00,000 US$/MWh or 3,30,000-4,60,000 €/MWh [60] at the average exchange rate of 0.755 US$/€ in 2010 [69]. As with NaS, this is based on a ratio between installed discharge capacity and storage capacity of 6h. It should be noted that PHS is by far the most used grid-connected electricity storage technology with 153 GW out of 154 GW globally [70]. Only two CAES plants are in operation – albeit both in the >100MW size range [70]. NaS experienced a ten-fold increased from on 2,000 to 2,006 thus a technology with significant development [70].

Efficiencies given in [71] for PHS are 70-80%, [60] list cycle efficiencies as 80-82% and [72] list efficiencies from 76 to 85% depending on design.

Comments on thermal storage

All thermal storages are calculated based on a ΔT=60K corresponding to a specific contents of 70 kWh/m^3. The Danish Energy Agency[71] list specific contents for large steel storage tanks and seasonal pit storages as 60-80 kWh/m^3.

The 6200 m^3 tank is an actual storage of Skagen district heating company in Denmark. The Danish Energy Agency lists costs for large steel tanks for district heating at 160-260€/m^3 [71] corresponding to 2,300-3,700 €/ MWh.

[3] Cost, insurance and freight.

Costs of the 160 litre and the 4 m^3 tanks are based on actual bids from a supplier including installation costs. The Danish Energy Agency lists small tanks (150-500 l) at around 4€/ l - though this cost does not include installation costs [71]. This corresponds to 57,000€/MWh

Comment on gas storage

The costs are based on a gas cavern. For comparison, a five-cavern plant in Denmark with 5*100 million Nm^3 - equivalent to a total of 5.5 TWh - costs 254 M€ or 46€/MWh [71]

Comment on fuel storage

Storage costs vary according to local conditions including e.g. size and number of tanks, potential jetty construction, tank foundation details based on soil conditions. Based on actual tanks of Oiltanking Copenhagen, prices are in the 200-250 €/m^3 range.

Comment on production costs for renewable energy

As noted by [73], "cost projections [of wind, solar] are abundant [..] although with high uncertainties attached". Investigating data from the Danish Energy Authority and the Danish transmission system operator Energinet.dk on renewable energy technologies reveals a wide span of technology costs and thus production costs. The same technology costs are included from a 2012 assessment and a 2016 assessment to show how price expectations have changed with decreasing costs from on-shore wind - but increasing costs off-shore. Photo voltaics on the other hand have experienced a significant decrease over the same period of time.

For comparison, median scenarios for biomass prices in Denmark show costs of 6.2 €/GJ in 2015 and 7.1 €/GJ in 2030 [74] CIF[3] Danish harbour - giving a marginal fuel cost of 50-57€/MWh for a biomass condensing power plant with an efficiency of 45%. Coal - with a September 2016 price of approximately 72 US$/t [75] (64€/t) - has a fuel cost of approximately 18€/MWh based on a condensing mode power plant with an efficiency of 45%. Average CIF prices for industry in Denmark in 2015 were 382 DKK/t [76] or 50€/t - thus a fuel cost of electricity of 14€/MWh if coal prices for power plant are equal to coal prices for industrial coal users.

In Figure 6, renewable electricity production is shown as a band from 30 to 50 €/MWh.

Table 1: Characteristics for storage technologies.

Storage type	Investment cost [€/MWh storage capapcity]	Fixed O&M [% of investment]	Lifetime [Years]	Annual costs [€/MWh storage capacity]	Cycle efficiency
Electricity – PHS [59]	175000	0.5	50	4387	0.80
Electricity – NaS [60]	600000	0.5	30	33612	0.85
Electricity – CAES [20]	125000	–	–	–	–
Electricity – Tesla [61]	660000	–	–	–	–
Thermal – pit [62]	500	0.5	30	28.0	0.85
Thermal – large tank [63]	2500	0.5	25	156	0.95
Thermal – 4000 l [64]	24000	–	–	–	–
Thermal – 160 l [64]	180000	–	–	–	–
Gas [65]	60	0.5	50	2.6	0.98
Liquid [66]	20	0.5	30	1.1	1.00

Table 2: Wind and photo voltaic technology costs and production assumptions. Total production costs are calculated based on the other columns (and are thus not calculated by the stated references). Investment costs are calculated as an annuity using a discount rate of 3 percent. Years (2015 and 2030) refer to prognoses for the two years.

	Investment cost [€/MW]	Technical lifetime [Years]	Capacity factor	Fixed O&M [€/MW]	Variable O&M [€/MWh]	Total production cost		Source
						[€/MWh]	[DKK/MWh]	
Wind – Large on-shore 2015	1400000	20	0.337	n.a.	14	40	298	[77]
Wind – Large on-shore 2030	1290000	20	0.365	n.a.	12	34	254	[77]
Wind – Large off-shore 2015	3100000	20	0.457	n.a.	19	61	457	[77]
Wind – Large off-shore 2030	2300000	25	0.502	n.a.	16	49	366	[77]
Grid-connected PV 2015	2000000	30	0.091	n.a.	34	216	1620	[77]
Wind – Large on-shore 2015	1070000	25	0.37	25600	2.8	31	236	[78]
Wind – Large on-shore 2030	910000	30	0.38	22300	2.3	29	217	[78]
Wind – Large off-shore 2015	3500000	25	0.5	72600	5.5	72	542	[78]
Wind – Large off-shore 2030	2700000	30	0.53	55000	3.9	58	436	[78]
Large grid-connected PV 2015	1200000	30	0.122	12000	0	93	697	[79]
Large grid-connected PV 2030	820000	40	0.140	8160	0	72	539	[79]

LIST OF PEER-REVIEWED JOURNAL ARTICLES, BOOK CHAPTERS, PHD DISSERTATIONS AND DEFINITION PAPERS

Journal articles:

Lund, H., Østergaard, P.A., Chang, M., Werner, S., Svendsen, S., Sorknæs, P., Thorsen, J.E., Hvelplund, F., Mortensen, B.O.G., Mathiesen, B.V., Bojesen, C., Duic, N., Zhang, X.; Möller, B.: “The status of 4th generation district heating: Research and results”, Energy vol. 164, 1 December 2018, pp. 147-159

Sandvall A.F., Ahlgren E.O.; Ekvall T.: ”Cost-efficiency of urban heating strategies – Modelling scale effects of low-energy building heat supply”, Energy Strategy Reviews 18, 2017, pp. 212-223

Sandvall A.F., Ahlgren E.O.; Ekvall T.: ”Low-energy buildings heat supply - Modelling of energy systems and carbon emissions impacts”, Energy Policy 111, 2017, pp. 371-382

Thellufsen, J.Z.; Lund, H.: “Cross-border versus cross-sector interconnectivity in renewable energy systems”, Energy 124, 19 February 2017, pp. 492-501

Werner, S.: ”International review of district heating and cooling”, Energy vol. 137, 15 October 2017, pp. 617-631

Hvelplund, F., Østergaard, P.A.; Meyer, N.I.: ”Incentives and barriers for wind power expansion and system integration in Denmark”, Energy Policy Volume 107, August 2017, pp. 573-584

David, A.; Mathiesen, B. V.; Averfalk, H.; Werner, S.; Lund, H.: ”Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems”, Energies, 10(4), 578, Published: 22 April 2017

Lund, H.; Østergaard, P.A.; Connolly, D.; Mathiesen, B.V.: ”Smart energy and smart energy systems”, Energy vol. 137, 15 October 2017, pp. 556-565

Averfalk, H.; Ingvarsson, P.; Persson, U.; Gong, M.; Werner, S.: ”Large heat pumps in Swedish district heating systems”, Renewable and Sustainable Energy Reviews, Volume 79, November 2017, pp. 1275-1284

Lund, R.; Østergaard, D. S.; Yang, X.; Mathiesen, B. V.: ” Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective”, International Journal of Sustainable Energy Planning and Management, Vol 12, 2017, pp. 5-18

Hvelplund, F.; Djørup, S.: ”Multilevel policies for radical transition: Governance for a 100% renewable energy system”, Environment and Planning C: Politics and Space 0(0), pp. 1-24, The Author(s) 2017 Reprints and permissions, SAGE Journals

Djørup, S. R.; Hvelplund, F. K.: “District Heating as Part of a European Energy Union”, HOT/COOL - International Magazine on District Heating and Cooling, Vol. 4. December 2016

Lund, R.; Ilic, D.D.; Trygg. L.: ”Socioeconomic potential for introducing large-scale heat pumps in district heating in Denmark”, Journal of Cleaner Production, Volume 139, 15 December 2016, pp. 219-229

Karlsson, K.B.; Petrovic, S.N.; Næraa, R.: “Heat supply planning for the ecological housing community”, Munksøgård, Energy, Volume 115, Part 3, 15 November, pp. 1733-1747

Petrovic, S.N.; Karlsson, K.B.: “Residential heat pumps in the future Danish energy system”, Energy, Vol. 114, 1 November 2016, pp. 787-797

Lund, H., Østergaard, P.A., Connolly, D., Ridjan, I., Mathiesen, B.V., Hvelplund, F., Thellufsen, J.Z.; Sorknæs, P.: “Energy Storage and Smart Energy Systems”, International Journal of Sustainable Energy Planning and Management Vol. 11 2016, pp. 3-14

Averfalk. H.; Werner, S.: “Essential improvements in future district heating systems”, The 15th International Symposium on District Heating and Cooling, September 4-7, 2016, Seoul, Republic of Korea (South Korea) – Symposium paper

Lund, H.; Duic, N.; Østergaard. P.A.; Mathiesen, B.V.: “Smart energy systems and 4th generation district heating”, Energy, Vol 110, 1 September 2016, pp. 1-4

Østergaard, D.S.; Svendsen, S.: ”Theoretical overview of heating power and necessary heating supply temperatures in typical Danish single-family houses from the 1900s”, Article in: Energy and Buildings, Vol. 126, 15 August 2016, pp. 375-383

Østergaard, D.S.; Svendsen, S.: ”Case study of low-temperature heating in an existing single-family house?A test of methods for simulation of heating system temperatures”, Article in: Energy and Buildings, Vol. 126, 15 August 2016, pp. 535-544

Yang, X.; Li, H.; Svendsen, S.: ” Energy, economy and exergy evaluations of the solutions for supplying domestic hot water from low-temperature district heating in Denmark”, Energy Conversion and Management, Vol. 122, 15 August 2016, pp. 142–152

Yang, X.; Li, H.; Svendsen, S.: ”Evaluations of different domestic hot water preparing methods with ultra- low-temperature district heating”, Energy Journal, Vol. 109, 15 August 2016, pp. 248–259

Connolly, D.; Lund, H.; Mathiesen, B.V.: “Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union”, Article in Renewable and Sustainable Energy Reviews, Vol. 60, July 2016, pp. 1634-1653

Bach, B.; Werling, J.; Ommen, T.; Münster, M.; Morales, J.M.; Elmegaard, B.: “Integration of large-scale heat pumps in the district heating systems of Greater Copenhagen”, Article in Energy, Vol. 107, 15 July 2016, pp. 321-334

Hansen, K.; Connolly, D.; Lund, H.; Drysdale, D.; Thellufsen, J.Z.: “Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat”, Article in Energy, available online 20 June 2016

Grundahl, L.; Nielsen, S.; Lund, H.; Möller, B.: ”Comparison of district heating expansion potential based on consumer-economy or socio-economy”, Article in Energy, Available online 17 June 2016

Petrovic, S.; Karlsson, K.: “Ringkøbing-Skjern energy atlas for analysis of heat saving potentials in building stock”, Article in Energy, Available online 3 June 2016

Büchele, R.; Kranzl, L.; Müller, A.; Hummel, M.; Hartner, M.; Deng, Y.; Bons, M.: ”Comprehensive Assessment of the Potential for Efficient District Heating and Cooling and for High-Efficient Cogeneration in Austria”, Article in International Journal of Sustainable Energy Planning and Management, [S.l.], v. 10, p. 3- 20, June 2016

Razani, A.R.; Weidlich, I.: “A genetic algorithm technique to optimize the configuration of heat storage in DH networks”, Article in International Journal of Sustainable Energy Planning and Management, [S.l.], v. 10, p. 21-32, June 2016

Prina, M.G.; Cozzini, M.; Garegnani, G.; Moser, D.; Oberegger, U.F.; Vaccaro, R.; Sparber, W.: ”Smart energy systems applied at urban level: the case of the municipality of Bressanone-Brixen”, Article in International Journal of Sustainable Energy Planning and Management, [S.l.], v. 10, p. 33-52, June 2016

Østergaard, P.A.; Lund, H.; Mathiesen, B.V.: “Smart energy systems and 4th generation district heating”, Editorial in International Journal of Sustainable Energy Planning and Management, [S.l.], v. 10, p. 1-2, June 2016

Østergaard, D.S.; Svendsen, S.: ”Replacing critical radiators to increase the potential to use low- temperature district heating ? A case study of 4 Danish single-family houses from the 1930s”, Article in: Energy, Available online 7 May 2016

Yang, X.; Li, H.; Svendsen, S.: ”Alternative solutions for inhibiting Legionella in domestic hot water systems based on low-temperature district heating”, Building Services Engineering Research and Technologies, vol. 37 no. 4, 2016, pp. 468-478

Grohnheit, P.E.; Mortensen, B.O.G.: ”District heating as the infrastructure for competition among fuels and technologies”, Journal of Energy Challenges and Mechanics, Volume 3 (2016) issue 2, article 4, p. 64-69

Xiong, W.; Wang, Y.; Mathiesen, B.V.; Zhang, X.: “Case study of the constraints and potential contributions regarding wind curtailment in Northeast China”, Article in Energy, Available online 19 April 2016

Lund, R., Mohammadi, S.: “Choice of insulation standard for pipe networks in 4th generation district heating systems”, Article in Applied Thermal Engineering, Vol. 98, 5 April 2016, pp. 256-264

Østergaard, P.A.; Andersen, A.N.: ”Booster heat pumps and central heat pumps in district heating”, Article in Applied Energy, Available online 19 March 2016

Dominkovic, D.F.; Bacekovic, I.; Cosic, B.; Krajacic, G.; Pukšec, T.; Duic, N.; Markovska, N.: “Zero carbon energy system of South East Europe in 2050”, Article in Applied Energy, Available online 19 March 2016

Lund, R., Mathiesen, B.V.: “Large combined heat and power plants in sustainable energy systems”, Article in Applied Energy, Vol. 142, March 05, 2015, pp. 389-395

Lythcke-Jørgensen, C.; Ensinas, A.V.; Münster, M.; Haglind, F.: ”A methodology for designing flexible multi- generation systems”, Article in Energy, Available online 20 February 2016

Sandvall, A.F.; Ahlgren, E.O.; Ekvall, T.: ”System profitability of excess heat utilisation? A case-based modelling analysis”, Article in Energy, Vol. 97, 15 February 2016, pp. 424-434

Lund, R.; Persson, U.: ”Mapping of potential heat sources for heat pumps for district heating in Denmark”, Article in Energy, Available online 22 January 2016

Yang, X.; Li, H.; Svendsen, S.: ”Decentralized substations for low-temperature district heating with no Legionella risk, and low return temperatures”, Article in Energy, Available online 14 January 2016

Persson, U.; Münster, M.: ” Current and future prospects for heat recovery from waste in European district heating systems: A literature and data review”, Article in Energy, Available online 14 January 2016

Werner, S.: “European space cooling demands”, Article in Energy, 13 December 2015

Yang, X.; Li, H.; Svendsen, S.: ” Modelling and multi-scenario analysis for electric heat tracing system combined with low temperature district heating for domestic hot water supply”, Building Simulation, November 2015

Østergaard, P.A.: “Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations”, Article in Applied Energy, Vol. 154, 15 September 2015, pp. 921-933

Mortensen, B.O.G.: “Forsyningspligt og aftagepligt? Et offentligretligt studie”, i Trine Baumbach, Peter Blume & Michael Gøtze (red.): Ret på flere felter. Festskrift til Carsten Henrichsen, Jurist- og Økonomforbundets Forlag, 2015, s. 323-341

Mikulandric, R.; Krajacic, G.; Duic, N.; Khavin, G.; Lund, H.; Mathiesen, B.V.; Østergaard, P.A.: “Performance analysis of a hybrid district heating system: A Case Study of a Small Town in Croatia”, Journal of Sustainable Development of Energy, Water and Environment Systems, Vol. 3, Issue 3, 2015 pp. 282-302

Čulig-Tokić, D.: “Comparative analysis of the district heating systems of two towns in Croatia and Denmark”, Energy Journal, Vol. 92, 2015 pp. 435–443

Lund, R.; Mathiesen, B.V.: "Large combined heat and power plants in Sustainable Energy Systems" in Applied Energy, Vol. 142, 2015 pp. 389-395

Mathiesen, B.V.; Lund, H.; Connolly, D.; Wenzel, H.; Østergaard, P.A.; Möller, B.; Nielsen, S.; Ridjan, I.; Karnøe, P.; Sperling, K.; Hvelplund, F.: "Smart Energy Systems for coherent 100% renewable energy and transport solutions" in Applied Energy, Vol. 145, 2015, pp. 139–154

Mischke, P., Xiong, W.: "Mapping and benchmarking regional disparities in China's energy supply, transformation and end-use in 2010" in Applied Energy, Vol 143, 2015 pp. 359-369

Xiong, W.; Wang, Y.; Mathiesen, B.V.; Lund, H.; Zhang, X.: "Heat Roadmap China: New heat strategy to reduce energy consumption towards 2030" in Energy Journal, Vol 81, 1 March 2015, pp. 274–285

Sorknæs, P.; Lund, H.; Andersen, A.N.: "Future power market and sustainable energy solutions – The treatment of uncertainties in the daily operation of combined heat and power plants" in Applied Energy Vol. 144, 2015, p. 129–138

Chittum, A. and Østergaard, P.A.: "How Danish communal heat planning empowers municipalities and benefits individual consumers" in Energy Policy, vol. 74, pp. 465-474, November 2014

Connolly, D.; Mathiesen, B.V.: "A technical and economic analysis of one potential pathway to a 100% renewable energy system" in International Journal of Sustainable Energy Planning and Management, Vol. 1, 2014, pp. 7-28.

Connolly, D.; Mathiesen, B.V.; Ridjan, I.: "A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system" in Energy Journal Vol. 73, 14.08.2014, pp. 110-125.

Connolly, D., Lund, H.; Mathiesen, B.V.; Werner, S.; Möller, B.; Persson, U.; Boermans, T.; Trier, D.; Østergaard, P.A.; Nielsen, S.: "Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system" in Energy Policy, vol. 65, pp. 475-489

Li, H.; Svendsen, S.: "District Heating Network Design and Configuration Optimization with Genetic Algorithm" in Journal of Sustainable Development of Energy, Water and Environment Systems, Vol. 1, No. 4, 2013, pp. 291-303

Lund, H., Thellufsen, J.Z.; Aggerholm, S.; Wittchen, K.B.; Nielsen, S.; Mathiesen, B.V.; Möller, B.: "Heat Saving Strategies in Sustainable Smart Energy Systems" in International Journal of Sustainable Energy Planning and Management, Vol 4, pp. 3-16

Lund, H.; Werner, S.; Wiltshire, R.; Svendsen, S.; Thorsen, J.E.; Hvelplund, F.; Mathiesen, B.V.: "4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems" in Energy, vol. 68, pp. 1-11, April 2014

Markovska, N.; Klemeš, J.J.; Duic, N.; Guzović, Z.: "Sustainable development of energy, water and environment systems" in Applied Energy, Vol. 135, 2014, pp. 597–599.

Meyer, N.I.; Mathiesen, B.V.; Hvelplund, F.: "Barriers and Potential Solutions for Energy Renovation of Buildings in Denmark" in International Journal of Sustainable Energy Planning and Management, Vol. 1, 2014, pp. 59-66.

Mortensen, B.O.G.: "Legal Framework as a Core Element of District Cooling Success - The Case of Denmark" in Journal of Power and Energy Engineering, September 2014, Vol. 2, No 9, pp. 41-48

Persson U.; Möller, B.; Werner, S.: "Heat Roadmap Europe: Identifying strategic heat synergy regions" in Energy Policy, vol. 74, pp. 663-681, November 2014

Petrovic, S.; Karlsson, K.B.: "Danish heat atlas as a support tool for energy system models" in Energy Conversion and Management, vol. 87, pp. 1063–1076, November 2014

Petrovic, S.; Karlsson, K.B.: "Model for Determining Geographical Distribution of Heat Saving Potentials in Danish Building Stock" In ISPRS International Journal of Geo-Information. 2014; 3(1):143-165

Pukšec, T.; Mathiesen, B.V.; Novosel, T.; Duić, N.: "Assessing the impact of energy saving measures on the future energy demand and related GHG (greenhouse gas) emission reduction of Croatia" in Energy Journal, Vol. 76, 2014, pp. 198-209.

Ridjan, I.; Mathiesen, B.V.; Connolly, D.: "Synthetic fuel production costs by means of solid oxide electrolysis cells" in Energy Journal, Vol. 76, 01.11.2014, pp. 104-113

Sorknæs, P.; Lund, H.; Andersen, A.N.; Ritter, P.: "Small-scale combined heat and power as a balancing reserve for wind: The case of participation in the German secondary control reserve" in International Journal of Sustainable Energy Planning and Management, Vol 4, pp. 31-44

Xiong, W.; Zhu, G.; Zhang, D.; Zhang, X.: "Economic decision support tool of renewable energy for wind and PV power projects –IRPP model and its application" in Renewable Energy Resources, issue 4, pp. 65-70, 2013

Zhang, D.; Xiong, W.; Tang, C.; Liu, Z.; Zhang, X.: "Determining the appropriate amount of subsidies for wind power: The integrated renewable power planning (IRPP) model and its application in China" In Sustainable Energy Technologies and Assessments, Vol. 6, June 2014, pp. 141–148

Østergaard, P.A..; Lund, H.; Mathiesen, B.V.: "Energy system impacts of desalination in Jordan" in International Journal of Sustainable Energy Planning and Management, Vol. 1, 2014, pp. 29-40.

Sorknæs, P.; Andersen, A.N.; Tang, J.; Strøm, S.: "Market integration of wind power in electricity system balancing" in Energy Strategy Reviews, Vol 1(3), pp. 174-180

Lund, H.; Andersen, A.N.; Østergaard, P.A.; Mathiesen B.V.; Connolly, D.: "From Electricity Smart Grids to Smart Energy Systems - a market operation based approach and understanding" in Energy, vol.42(19) pp. 96-102, June 2012

Lund, H. and Hvelplund, F.: "The economic crisis and sustainable development: The design of job creation strategies by use of concrete institutional economics" in Energy, Vol 43 pp. 192-200

Book chapters/books:

Truelsen, P. Aa., Mortensen, B.O.G.; Christensen, L.: ”Varmeforsyningsloven med kommentarer”, Karnov Group 2018

Gadd H.; Werner S.: "Thermal energy storage systems for district heating and cooling". Chapter 18 in Cabeza (ed.), Advances in Thermal Energy Storage Systems, pp. 467-478. Woodhead publishing series in Energy 66, Cambridge 2015

Henrik Lund (With contribution by F. Hvelplund, PA Østergaard, B. Möller, BV Mathiesen, D. Connolly, and AN Andersen): “Analysis: Smart Energy Systems and Infrastructures” Chapter 6 in “Renewable Energy Systems (Second Edition). A Smart Energy Systems. In Approach to the Choice and Modeling of 100% Renewable Solutions”. Academic Press, 2014, pp. 131-184.

Mortensen, B.O.G.: "Udtrædelsesgodtgørelse" i Erling Eide, Henrik Lando og Endre Stavang (red.): Rettsøkonomi i nordiske dommer. In Skriftsserie 197/2014, pp. 175-197

Mortensen, B.O.G.: "Fjernvarme – En monopolsektor i konkurrence". Article in "Festskrift til Jens Fejø", Jurist og Økonomforbundets Forlag, 2012, pp. 299-310

Mortensen, B.O.G.: "Lokalitetsprincippet og kommunal forsyningsvirksomhed" In Hans Viggo Godsk Pedersen (red.): Juridiske emner ved Syddansk Universitet 2013, Jurist- og Økonomforbundets Forlag, pp. 309-325

Mortensen, B.O.G.: "Fjernkøling". In "Offentlig - privat; i hurudana strukturer" by Jan-Erik Helenelund, Ilpo Luoto, Niina Mäntylä og Kristian Siikavirta (red.). Published as Festskrift til Eija Mäkinen, Universitas Wasaensis (Finland), Acta Wasaensia No 265, pp. 452-467, 2012.

Mortensen, B.O.G.: "Forbrugerindflydelse i fjernvarmesektoren - en barriere for forsyning ud over kommunegrænsen?" in Festskrift til Nis Jul Clausen, pp. 295-306, Jurist- og Økonomforbundets Forlag 2013

PhD dissertations:

Lars Grundahl: District Heating Potential and a Danish Heat Atlas Based on Metered Heat Demand Data, Aalborg University, December 2017

Michael Herborn: Chapter 1 A of the heat supply act and its impact upon municipal engagement in strategic energy planning, University of Southern Denmark, September 2017

Rasmus Søgaard Lund: Heating Strategies in a Renewable Energy Transition, Aalborg University, May 2017

Søren Djørup: Fjernvarme i forandring - omstilling til vedvarende energi i økonomisk perspektiv / Change in district heating - transition to renewable energy from an economic perspective, Aalborg University, November 2016

Soma Mohammadi: Conversion of Existing District Heating Grids to Low-Temperature Operation and Extension to new Areas of Buildings, Aalborg University, October 2016

Stefan Petrovic: Geographic Information Systems and Energy System modelling for Analysis of renewable Energy Systems, Technical University of Denmark, October 2016

Weiming Xiong: Development of the China Renewable Electricity Planning and Operations Model (REPO) and its application, Tsinghua University, September 2016

Xiaochen Yang: Improved technologies remove risk of legionella in low temperature district heating, Technical University of Denmark, June 2016

Peter Sorknæs: "Bidding and operation strategies in future energy markets? The transition of small district heating plants into market-based smart energy systems", Aalborg University, July 2015

Urban Persson: "District heating in future Europe: Modelling expansion potentials and mapping heat synergy regions", Chalmers University of Technology, January 2015

Definition papers:

"Scientific excellence within research in future district heating systems and technologies", 4DH International Scientific Panel and Advisory Board, August 2015

PLENARY KEYNOTE SPEAKERS

Henrik Lund is Professor in Energy Planning at Aalborg University, Head of the 4DH Research Centre and Editor-in-Chief of ENERGY – The International Journal of Elsevier. Henrik Lund has more than 30 years of experience in research and involvement in Danish energy planning and policy making. Among others, he has been involved in the making of the Danish Society of Engineers' proposal for a future 100% Renewable Energy Plan for Denmark. He is the main developer of the advanced energy system analysis software EnergyPLAN. Henrik Lund is on the Thomson Reuters list of the most highly cited researches in the world within the topic of engineering and has contributed to more than 300 books and articles.
Henrik Lund will give a speech on **The Status of 4th Generation District Heating: Research and Results.**

Lily Riahi works as an advisor on Sustainable Energy in Cities for the United Nations Environment Program (UNEP). She is the report author of the UNEP flagship report 'District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy." She is currently leading the UNEP led SE4All Global District Energy in Cities Initiative which is working to improve energy efficiency and scale up renewable energy through modern district energy systems.
Previously, Lily Riahi worked as a Policy Advisor for REN21, the Renewable Energy Policy Network for the 21st Century and as an analyst for the office of Dr. Hermann Scheer, MP, at the German Parliament in Berlin, with a focus on the political process to establish the International Renewable Energy Agency (IRENA) and the transfer of renewable energy policy best practice to other jurisdictions in the US and Canada
Lily Riahi will give a speech on **District Energy in Cities: Global Perspective on Unlocking the Potential for District Heating and Cooling**.

Mark Z. Jacobson is Director of the Atmosphere/ Energy Program and Professor of Civil and Environmental Engineering at Stanford University. He is also a Senior Fellow of the Woods Institute for the Environment and of the Precourt Institute for Energy. He received the 2005 AMS Henry G. Houghton Award and the 2013 AGU Ascent Award for his work on black carbon climate impacts and the 2013 Global Green Policy Design Award for developing state and country energy plans. In 2015, he received a Cozzarelli Prize from the Proceedings of the National Academy of Sciences for his work on the grid integration of 100% wind, water and solar energy systems. He has served on an advisory committee to the U.S. Secretary of Energy.
Mark Z. Jacobson will give a speech on **Transitioning towns, cities, and countries to 100% clean, renewable energy for all purposes.**

Xiliang Zhang is Professor and Director of the Institute of Energy, Environment and Economy at Tsinghua University and Deputy Director at the Tsinghua-Rio Tinto RES Research Centre. Professor Zhang has been a lead author of the IPCC Climate Change Assessment Reports.
Xiliang Zhang will give a speech on **District heating in China: status quo, challenges and perspective.**

Neven Duić is Pofessor and Energy Management Chair at the Department of Energy, Power Engineering and Environment, at the University of Zagreb. He has organised a series of conferences on Sustainable Development of Energy, Water and Environment Systems and has been a member of organising, scientific and programming committees of more than 40 research conferences.
Neven Duić will give a speech **on District heating and 4th generation district heating in Eastern Europe.**

ABSTRACTS

Plenary Keynote: The Status of 4th Generation District Heating: Research and Results

Professor Henrik Lund, Department of Planning, Aalborg University,lund@plan.aau.dk

This presentation focuses on the status of 4th Generation District Heating (4GDH) and presents the research and results of the 4DH Research Centre (4DH). Approximately 140 publications including 10 PhD theses are a direct result of 4DH and additional 50 papers were published in special issues from the International Conferences on Smart Energy Systems and 4th Generation District Heating, which were hosted by 4DH.

The transition from current energy systems to future sustainable energy solutions, including 100 per cent renewable energy (RE) systems, requires a coherent approach that integrates the different components of the energy system and exploits synergies through sector integration. District heating and cooling can have an important role to play in such systems, but the technologies must undergo a generational shift for their potentials to be fully exploited.

Unlike the previous three generations, the development of 4GDH involves balancing the energy supply with energy conservation and thus meeting the challenge of supplying increasingly more energy efficient buildings with space heating and domestic hot water (DHW), while reducing losses in district heating (DH) grids. Furthermore, 4GDH involves strategic and innovative planning and the integration of DH into the operation of smart energy systems. Following a review of recent 4GDH research, this presentation quantifies the costs and benefits of 4GDH in future sustainable energy systems. Costs involve an upgrade of heating systems and of the operation of the distribution grids, while benefits are lower grid losses, a better utilization of low-temperature heat sources and improved efficiency in the production compared to previous district heating systems. It is quantified how benefits exceed costs by a safe margin with the benefits of systems integration being the most important.

Plenary Keynote: District Energy in Cities: Global Perspective on Unlocking the Potential for District Heating and Cooling

Lily Riahi, Advisor on Sustainable Energy in Cities, UN Environment, lily.riahi@un.org

In 2014, the District Energy in Cities Initiatives (DES Initiative) was launched by UN Environment as part of the Global Efficiency Accelerator Platform at the New York Climate Summit, in recognition of the potential this technology option has to contribute toward the doubling of the global rate of energy efficiency and the objective of achieving sustainable energy for all. In 2015, the UN Environment report 'District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy' was launched, providing a best practice guide and toolkit based on research in low-carbon cities based on interviews, surveys, and consultations with close to 150 experts and stakeholders from around the world.

Since then, these lessons and methodologies have been used to engage with more than 15 cities and 14 national governments to carry out both rapid and in-depth assessments. These involve area mapping, policy analysis, technical project identification and appraisal and strategic planning development. The aim is to both secure project implementation (through (pre-) feasibility assessments, business model development, and procurement models) and encourage enabling frameworks in terms of policies, legislation, and financing at both the national and local level. By doing so, tools and methodologies are developed that can support other countries and cities looking towards implementing and supporting the development of district heating and cooling. This presentation gives an overview of the District Energy in Cities Initiative activities up to date, and the development of the approaches, tools and methodologies that have been used.

Session 1: Smart Energy Systems

Benedetto Nastasi is an architectural engineer and energy planner. His research focuses on the role of Eco-Fuels in transition towards a low carbon city and society, in a new relation between urban and rural environment in the energy-planning field. Benedetto Nastasi is passionate about Hydrogen Economy and is an expert of Sustainable Energy and Climate Action Plans, renewable energy technologies and their integration into urban and agricultural planning.

Synthetic fuels potential by Power-To-Gas integration at National level for enhancing energy independency

Benedetto Nastasi[1] *(presenter), PhD, Michel Noussan*[2]*, PhD*
[1] *Department of Architectural Engineering & Technology, TU Delft University of technology, Julianalaan 134 – 2628BX Delft, The Netherlands, benedetto.nastasi@outlook.com*
[2] *Department of Energy, Politecnico di Torino*

Keywords: energy storage, hydrogen economy, power to gas, cross-country exchange, energy transition, renewable electricity excess.

Cross-Country energy exchanges are becoming a crucial point of discussion to harmonize National energy security goals and the ongoing construction of the Pan-European energy policy. Import-export flows and the value of their ratio are of interest for policy makers assessing the National Energy System performance and, subsequently, influence on the energy market. Especially, at Power Grid level, the drivers to increase or reduce the quantity of electricity exchanged between two or more Countries belong to the need for matching energy consumption and supply together with their prices of demand and offer. The prioritization of certain energy sources such as wind and sun by means of incentive schemes defined the current energy potential of a Country and determined its electricity excess profile too. Synthetic fuels are conceived as further strategy to handle the National renewable electricity excess by providing medium-term energy storage option, the creation of an energy carrier able to link electricity sector with heating and/or transport ones and, last but least, promoting decarbonisation of the energy systems. This paper analysed the actual hourly import/export electricity flows of Italy between 2012 and 2017 together with the electricity generation by source, the objective being the potential in synthetizing Hydrogen by means of electrolytic process to support increasing shares of unprogrammable renewables in the Italian energy mix. The amount of Hydrogen as well as its effect on the energy independency of the Country, once the fuel is converted back to electricity or to both electricity and heating, was assessed. Further projections were built on the use of the synthetic fuel for feeding new pathways of transportation such as Fuel Cell-based vehicles. Finally, the contribution of storing electricity excess and re-use when the internal production is lower than the internal demand affects the Primary Energy Factor of the National Power Grid. This effect is computed on hourly base in comparison with real data of the same time interval.

Hanmin Cai is a PhD fellow at the Technical University of Denmark. He is working on demand side management to assist heat and electric network operation and is involved in the Nordhavn project.

Fuel shift for improving urban integrated energy system operation and efficiency

Mr. Hanmin Cai (*presenter*), *Dr. Shi You, Dr. Henrik W. Binder*
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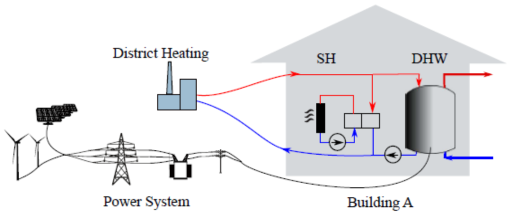
Keywords: energy integration, domestic hot water, fuel-shift, low-temperature-district-heating, flexibility, ancillary service

A large amount of literature has been focusing on low-temperature district heating (LTDH) in order to reduce heat loss reduction and facilitate renewable energy integration. Yet, LTDH alone is insufficient for domestic water heating, which requires 50 °C for circulation and 60 °C as set point temperature for the storage tank due to hygiene concern. Our work from last year's 4dh conference contributed to this research area [1] and this abstract intends to extend our previous effort.
Previous analysis on fuel shift technology shows substantial benefits and the potential to provide more services in an integrated energy system. It was based on a hypothetical district with 23 terraced single-family houses supplied by both a low-temperature district heating (LTDH) network and a low-voltage network (LVN), as shown in Fig 1 to Fig 4. It was shown that district heating network (DHN) losses can be reduced by 35% if the supply temperature is reduced from 70 °C to 50 °C, but the LVN peak power will have to be increased by up to 2% using heat boosting. It further aggregated EHBs to provide a fuel shift (FS) service for the DHN. The results show that while LVN peak power was increased by up to 4.3%, the basic power production and peak boiler usage for DHN could be reduced by as much as 15% and 48%, respectively. In summary, lower supply, temperatures and intelligent components can improve system efficiency and turn the DHN into an integrated part of a SES.
We will extend previous analysis and further study fuel-shift solution and investigate the possibility to provide ancillary services to distribution network. We will conclude the research with fuel-shift feasibility and implications for industrial application.



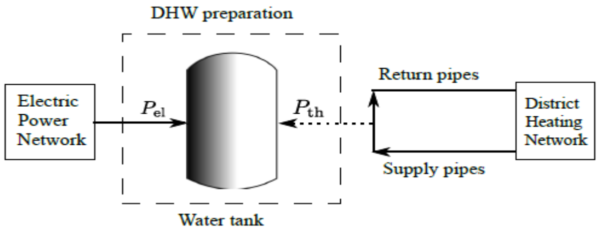
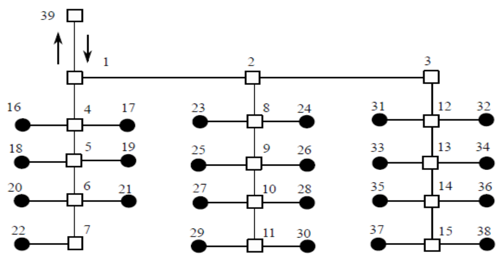


Figure 1. Building's connection to heat and power system and its energy sources

Figure 2. Electric heat booster



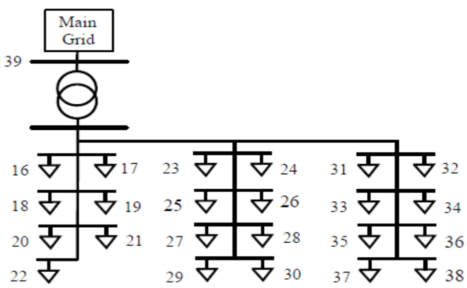


Figure 3.District heating network

Figure 4. Low voltage distribution network

[1] Cai, H., You, S., Wang, J., Bindner, H.W. and Klyapovskiy, S., 2018. Technical assessment of electric heat boosters in low-temperature district heating based on combined heat and power analysis. *Energy*, *150*, pp.938-949.

Andrei David is a PhD fellow in the Sustainable Energy Planning Research Group at Aalborg University. His research profile centers on the cross-sector integration and synergies between energy system infrastructures and energy storages. He is working on topics related to power-to-heat and power-to-gas, energy system analysis and modelling of 100% renewable energy systems, with a focus on technology pathways for the production of electrofuels.

Techno-economic analysis of electrofuel production in a Danish Smart Energy System

Andrei David (presenter) PhD Fellow, Iva Ridjan Skov, Assistant Professor, Brian Vad Mathiesen, Professor
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The Smart Energy System accounts for the use of electrofuels and their intermediaries (such as biogas and syngas) as a critical way to balance and provide flexibility in a future 100% renewable energy system in Denmark. The Smart Energy System operation of the electrolysers is important, since these are expected to absorb the excess renewable electricity produced on particularly windy or sunny days and offer the energy system the needed flexibility by storing excess electricity as gaseous or liquid fuels.
The type of fuels, as well as the pathways used for producing them rely on combination of technologies, of which not all are demonstrated or available on a commercial scale, making it a difficult task to quantify cost efficient synergies. This defines the aim of this study, which is to quantify the synergies between the technology combinations for electrofuel production that can enable reductions in the energy system costs, as well as and fuel costs. In the present study, the analysed fuels are methane, methanol/DME and kerosene, each obtained through carefully selected technology pathways.
The results show that if the electrolysers function on a stop and start basis, with higher installed capacities and hydrogen storage, the costs of the fuels produced are on average 10% higher than the costs of the fuels produced through the same technology pathways but on a continuous basis and with lower electrolyser capacities. In both types of operation, the use of synergies between the components has the potential of further reducing the costs. The heat from the methanation or chemical synthesis process used by the solid-oxide electrolysers can increase its efficiency by 10-12% and reflect in the final cost of the fuels with a reduction of 5-15% depending on the type of fuel produced. This demonstrates that higher capacities for electrolysers with intermittent operation and synergies between their components would only make fuels sensibly more expensive, but in an overall energy system context, such an operation mode might save society from unwanted costs related to excess electricity production.

Sara Bellocchi is currently conducting research on sustainable mobility within smart energy systems contexts.

On integrating electric vehicles into Smart Energy Systems: Italy and Germany in comparison

Sara Bellocchi[1] *(presenter), Kai Klöckner*[3]*, Michele Manno*[1]*, Michel Noussan*[2]
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[3] *School of Business and Economics Chair of Management Accounting, RWTH Aachen University, Aachen, Germany*

Over the last decade, electric vehicles have gained ever-increasing interest as a promising alternative to conventional road transport able to reduce pollutant and greenhouse gas emissions and shift the economy away from oil products. Electric vehicles can play a major role in the transition towards Smart Energy Systems, thanks to the synergies that can be implemented with the other sectors, in particular in the challenges related to energy storage. However, the related increase in electricity demand inevitably affects the strategic planning of the overall energy system as well as the definition of the optimal power generation mix.
With this respect, the impact of electric vehicles may vary significantly depending on the country according to composition of both the total primary energy supply and the electricity generation sector. In this study, Italy and Germany are compared to highlight how a similarity in their renewables shares not necessarily leads to a CO_2 emissions reduction, when electric vehicles penetrate energy systems whose electricity generation sector relies heavily on carbon intensive primary energy sources. Different energy scenarios are simulated with the help of EnergyPLAN software assuming progressively increasing shares of renewable energy in the electricity generation mix. Finally, critical environmental and economic indicators are used to assess to what extent electric vehicles contribute to a sustainable mobility that also supports renewable energy integration.

Timo Kannengiesser is a PhD fellow at RWTH Aachen University and works at Forschungszentrum Juelich in the Institute of Electrochemical Process Engineering (IEK-3), Department for Process and Systems Analysis. The thesis is carried out in cooperation with the German distribution network operator Westnetz GmbH. Timo Kannengiesser received his Master from RWTH Aachen University in Sustainable Energy Supply.

Optimization of Urban Energy Supply Systems Considering Various Sector-Coupling Options for Different Penetration Rates of Battery Electric Vehicles

Timo Kannengiesser[1] (presenter), Peter Stenzel[1], Peter Markewitz[1], Stefan Nykamp[3], Klaus Peters[3], Fabian Schütz[3], Martin Robinius[1], Detlef Stolten[1,2]
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Keywords: MILP, design optimization, operation optimization, urban district optimization, district heating, district cooling, transport demand model

Urban districts have a high potential to reduce greenhouse gas (GHG) emissions by increasing the energy efficiency by implementation of microgrids, which include various sector-coupling options. To find a cost optimal urban energy supply system this paper analyses different scenarios and the resulting effects on energy demand, structure of power generation and transmission system as well as energy system costs. The analysis is carried out considering a specific urban district in Germany as a case study.
A mixed-integer linear programming approach is used to design a cost optimal technology configuration on district level as well as a cost optimal grid configuration (district heat/ cooling) for a specific urban district. Based on the chosen technology configuration the optimal operation of generation technologies, storage technologies and energy grids is determined in the district. Furthermore, the potential of local heating and cooling in the district is analyzed related to the cost optimal results. The total energy flows are calculated in a time resolution of one hour and in a spatial resolution of 18 building nodes for one year. The total annual discounted energy system costs consist of fixed and capacity dependent investment costs and fixed and variable operating costs of the installed technologies. Furthermore, traffic demand profiles for the urban district are synthesized in a temporal resolution of one hour and the additional building specific electricity load is determined for charging electric vehicles. The integration of the battery electric vehicles is investigated scenario based.

Session 2: Future district heating production and systems

Richard Pieter van Leeuwen is professor in Sustainable Energy Systems at Saxion University of Applied Sciences. The research group investigates system planning and integration of renewable energy; smart grid control and power-to-heat integration; bio-energy conversion and nutrient recovery; as well as waste heat and heat pump systems integration.

Integration of waste heat and renewables into district heating systems in East-Netherlands

Richard Pieter van Leeuwen, Dr. MSc. (presenter), Sandra Wijnant-Timmerman, MSc., John van den Hof, Dr.,
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Keywords: heat transition, renewable energy integration, district heating, waste heat utilization, 4th generation district heating.

More than 90% of building heat consumption in The Netherlands relies on the use of natural gas, predominantly coming from natural gas fields in the Northern part of the country. Although reserves are not yet fully depleted, a number of severe earthquakes due to the loss of pressure within the gas fields has caused public unrest and recently forced a political decision to move away from the use of natural gas. Provincial and regional energy planning working groups are challenged to include plans for municipal and industrial “heat transition”: from natural gas towards renewable heating systems.
The province Overijssel in the Eastern part of the Netherlands moves forward with a coordinated heat transition initiative which includes district heating systems and individual heating system solutions for buildings and industry. Within the framework of the Interreg project WIEfm, Saxion University of Applied Sciences investigates a number of bottom up initiatives involving the use of industrial waste heat for municipal district heating systems (Hengelo industrial area and Wezep municipality), the use of heat from biomass combustion (Nijmegen Wolfskuil district and Almelo city) and the use of heat pumps, surface water and underground thermal sources as part of a district heating and cooling system (Deventer).
Besides technical challenges that are different for each case, the cases have in common a difficult economic feasibility due to the low price of heat for reference technologies. To overcome this challenge, each case adopted its own approach in order to find solutions and to gain public and municipal support.
In our contribution for the 4DH conference, we introduce the provincial heat transition plan and the investigated cases. We explain the technical challenges for the cases and present the main solutions and results of investigations. In addition, we explain business case and organizational challenges in relation to public-private cooperation and how these challenges are addressed by the initiatives. Last, we draw conclusions for these initiatives and provide an outlook for future initiatives within the provincial heat transition plan.

Hanne Kauko works as research scientist at SINTEF Energy Research. She works primarily with thermal system modelling and thermal storage. Her fields of interest include industrial clusters, refrigeration and heat pumping.

Thermal storage and optimal control for improved utilization of industrial waste heat in district heating

Hanne Kauko[1] *(presenter), Brage Rugstad Knudsen*[1] *and Terje Sund-Olsen*[2]
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[2] *Mo Fjernvarme AS, Norway*

Keywords: district heating, industrial waste heat recovery, thermal system modelling, thermal storage, predictive control

Mo Fjernvarme is a district heating supplier in Mo i Rana, Norway, with 90 % of the heat production being based on waste heat recovery from off-gases of a nearby ferrosilicon production plant. The total annual amount of available waste heat exceeds by far the heating demand in Mo i Rana; however, due to strong variations in both availability and demand of heat, auxiliary heat sources are needed to cover the peak demands. The occurrence of peak heating demands is fully predictable, whereas the variation in the waste heat availability is more arbitrary. The applied peak heating sources include combustion of industrial CO-gas, electricity, and in extreme situations light fuel oil. Even if the use of peak heating sources is generally low, it constitutes a significant share of total costs and emissions for the heat production.

In this context, Mo Fjernvarme is currently exploring opportunities for utilizing a thermal storage tank to shift the load from high to low demand periods and hence to reduce the use of peak heating sources. Due to the large and rapid variations in the demand and availability of heat, efficient control and operation of such a storage tank may be challenging, though important to fully utilize its potential.

In this work, we apply the dynamic simulation program Dymola and the object-oriented modelling language Modelica to study the potential of thermal storage in the described district heating system in Mo i Rana, using real data for heat production and demand. With dynamic modelling, the ability of the thermal storage system to respond to the rapid changes in availability and demand of heat can be evaluated. We elaborate on different control strategies, in particular using model predictive control, as a means of exploiting predictable time-variations in heat supply and demand, to ensure consistent operation of the thermal storage system and improve robustness against contingencies in operation. The goal of the work is to quantify the potential of thermal storage combined with predictive control to reduce costs and emissions associated with peak heating supply.

Alexandre Canet joined Cardiff University as a research associate to work on the FLEXIS project in 2017. He has a background in computer science and energy planning with more than four years of working experience from France, Denmark and the UK. His focus is on data science, integrated energy system, district heating and energy planning.

Feasibility of Transporting Industrial Waste Heat Over Long Distances: A Case Study in South Wales (UK)

Xiandong Xu, Alexandre Canet (presenter), Meysam Qadrdan
Institute of Energy, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK, caneta@cardiff.ac.uk

Keywords: CO2, long-distance, transport of heat, waste heat

The recovery and reuse of waste heat from large industries has the potential to support a cost-effective transition towards a secure and clean energy system. In Neath Port Talbot county (Wales, UK), more than 5,000 GWh/year of low grade heat are estimated to be wasted in a steel work. In comparison, the heat demand in the area is around 1,500 GWh/year[1]. However, supplying the heat demand through waste heat was shown to not be economically competitive against the construction of a new energy centre located closer to the demand. Hence, the challenges are to find more economical solutions to transport heat and/or transport heat to higher demand area to make the investment viable.

This paper performs a technical-economic analysis for the transport and supply of heat from the steel work to surrounding cities. Three configurations of heat transport are studied, two of which uses water as a carrier. The temperature difference between supply and return pipelines is 60°C in one configuration and 90°C in the other. The third configuration uses CO2 as a carrier (see Figure 1). For each of these configurations, a range of scenarios are created to investigate the impacts of heat demand and transport distance on the investment.

The results show that the CO2 configuration is more economically viable than the other two configurations, particularly when the distance is over 5 km. Depending on heat demand, using CO2 pipeline to carry heat over 100km distance could save between 20% to 35% of the capital cost compared to a conventional water-based heat transport pipeline with 60°C temperature difference. The increase of distance allows the non-conventional configurations to accommodate the additional costs resulting from the use of ancillary devices for heat extraction at demand side.

Under the current level of heat price and carbon tax, it is still difficult to deploy the transport of heat, as a two-year payback period is often targeted by industries. The CO2 configuration could unlock this potential by reducing the required number of pipelines for heat transport from two to one, which will significantly decrease the initial investment. Additionally, the CO2 configuration enables new revenue streams by

[1] http://www.heatroadmap.eu/peta4.php

providing a source of CO2 to the carbon utilisation industry (e.g. food production, synthetic fuel, etc.).

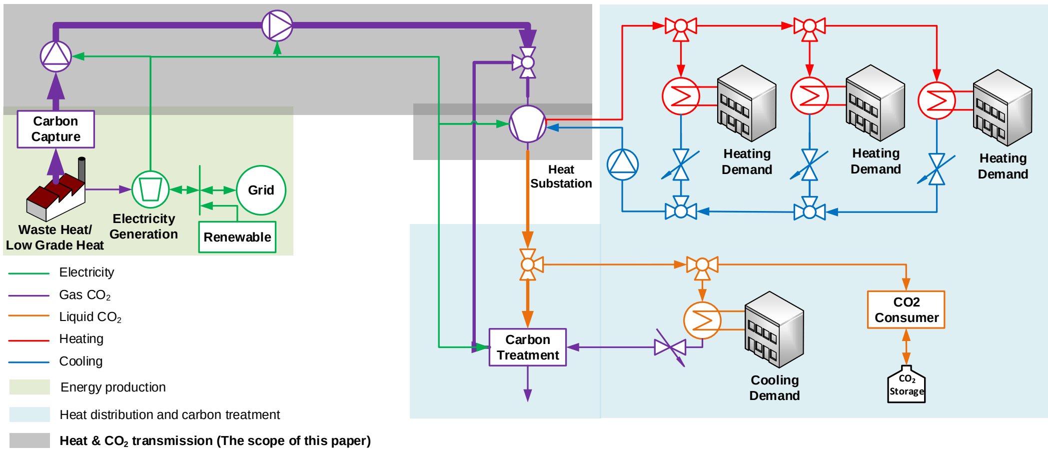

Figure 1: Schematic representing the CO_2 configuration and this paper's scope: transport of heat and CO_2

Johannes Pelda is a researcher in the field of energy systems in regional areas and district heating systems. His focus is on modelling and simulation of energy systems with open source and open data.

Methodology to evaluate and map the potential of waste heat from sewage water by using internationally available open data

Johannes Pelda[1] *(presenter), M. Eng.; S. Holler, Prof. Dr.-Ing.*[1]*; R. Stollnberger*[2]*, DI; R. Geyer*[2]*, MSc; E. Gebetsroither-Geringer*[2]*, Dr.; C. Sinclair*[3]*, BEng (Hons)*
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Keywords: waste heat, wastewater system, sewage water, heat potential, district heating system, open data

The integration of waste heat has been identified as a major research area in the European Union strategy on heating and cooling. In fact, the use of high-grade waste heat from combined heat and power stations (CHP), waste-to-energy plants or industrial processes, is state of the art. This paper presents the results of the MEMPHIS project that focused on developing and testing methodologies to assess the potential, and feasibility, of supplying urban areas with low-grade waste heat from the industrial and commercial sectors as well as from sewage networks. This paper introduces a novel methodology that provides an algorithm that is able to quantify, qualify and spatially allocate the waste heat potential of sewage systems on an urban district level, in all cases where real data from the sewage system does not exist or is not publicly available. The resulting sewage network model can be used to identify economically and ecologically suitable locations for extracting waste heat from sewage networks. The methodology has been applied to a city in Germany, where GIS data from the sewage network was provided to quantify and verify the accuracy of the developed methodology.
The research contributes to the wider integration of low-grade waste heat sources by providing an open data methodology that can be easily adapted to various types of cities and DH systems under changing boundary conditions. The research question that arises from the current state of the art is: how can a methodology quantify the highly distributed potential of waste heat from sewage systems, qualify it and allocate it to its source?
The newly developed methodology makes it possible to assesses the sewage heat potential on a city district level by applying a bottom-up approach which combines internationally available open data with key metrics, temperature profiles, ambient temperature fluctuations and heat losses in the sewage system. A generic sewage system model can then be generated using OpenStreetMap data and an algorithm

assesses all sewage disposal pathways to the wastewater treatment plants whilst also estimating wastewater flows along these paths. The mapped results show ecologically and economically feasible locations for exploitation of sewage heat. The accuracy of the modelled results has been analysed using a top-down approach, utilising real data from sewage plant records.

The results, from the application of the methodology for an example city, show that the methodology robustly calculated the paths from wastewater sources to the wastewater treatment plant as well as the wastewater volumetric flow. The research found that the generic system overlays the sewage system more accurately within areas that have a population density close to the average. The comparison with the real nominal diameter of the sewage network showed that the calculated volumetric flow appears to be highly underestimated and further work is required to investigate this and develop solutions. Despite small inaccuracies, the methodology is capable of presenting a good estimation of spatially distributed wastewater flows of the sewage system in the example city; it helps to assess the potential of waste heat sources of sewages quantitatively, qualitatively and spatially.

The MEMPHIS project is funded by the IEA Implementing Agreement on District Heating and Cooling including Combined Heat and Power within the Annex XII work programme.

Marcello Aprile has been Research Associate at the Department of Energy of Politecnico di Milano since 2016. He received his PhD in Energy Engineering in 2010. His main research interests are solar assisted air-conditioning and refrigeration, heat pumps, district heating and cooling, building physics, and HVAC systems for low-energy houses.

District power-to-heat/cool complemented by sewage heat recovery

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Keywords: district heating, district cooling, heat pump, sewage, simulation.

District heating and cooling (DHC), when combined with waste or renewable energy sources, is an environmentally sound alternative to individual heating and cooling systems in buildings. However, existing DHC networks mostly rely on economic and ecological energy sources like waste-to energy conversion plants, recovery of excess industrial heat and cool, and sea or lake water cooling, which are not available everywhere. To foster the diffusion of DHC, solutions relying on environmentally benign sources that are widely available, like solar and ambient heat, are thus of great interest. Electricity driven vapor compression heat pumps are suitable for heating and cooling especially in new buildings, characterized by low temperature heating systems. In the future European electricity grid dominated by renewable electricity, DHC based on heat pumps constitutes an extremely useful technology for converting decarbonized electricity into heat and cool while providing flexibility to the electricity system. When heating and cooling needs are not simultaneous, heat pumps must exchange heat with an external medium (e.g., air, water or ground). In this context, sewage heat recovery offers a thermodynamic advantage. On the one end, as compared to ground source heat pumps, sewage can supply renewable heat at a temperature above ground temperature. On the other hand, as compared to air-cooled chillers, sewage can serve as heat sink at a temperature below ambient air. Nevertheless, exchanging heat with sewage is not simple due to sludge accumulation that can deteriorate the heat exchanger effectiveness and eventually block the sewage flow, requiring both continuous screening of the sewage and periodic cleaning of the heat exchanger. In this work, the theoretical energy and economic performances of a small DHC network complemented by compression heat pump and sewage heat exchanger are assessed through dynamic, year-round energy simulations. The proposed system comprises also a water storage and a PV plant. The study stems from the operational experience on a DHC network in Budapest, in which a new sewage heat recovery system is in place and provided the experimental base for assessing main operational parameters of the sewage heat exchanger, like effectiveness, parasitic energy consumption and impact of cleaning. The potential of this solution is explored for a commercial district in Italy. It is found that the seasonal COP and EER of the proposes system are 3.3 and 3.8, while the seasonal COP and EER of the heat pump alone achieve 3.9 and 4.6, respectively. The difference in efficiency between overall system and heat pump is due to the parasitic energy of the pumps and the heat losses from the network. About 60% of the total parasitic energy is associated to sewage heat recovery. Nevertheless, the system can be cost-competitive with respect to a reference system based on distributed air-source/condensed, reversible electrical heat pumps. The levelized cost of energy of combined heating and cooling (LCOHC) is primarily affected by the correct dimensioning of the system. A minimum value of 2200 equivalent full load hours for combined heating and cooling (FLH) is found. Above this value, cost saving increases, reaching 10% for FLH equal to 2800. On-site PV, contributing for about 40% of the overall electricity demand, allows decreasing LCOHC by 6% under the price conditions set by the local electricity market.

Acknowledgements
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Session 3: Energy planning and planning tools

Bernd Möller is a professor in sustainable energy systems management in developing countries at the University of Flensburg. He also holds a 10% professorship at Aalborg University. His research embraces the geographical aspects of sustainable energy systems, where location determines potentials, costs, acceptance, and impact. For this purpose, extensive geo-information systems are being developed to improve the quantitative information base and to facilitate dissemination.

A Global Spatial Model to Identify Opportunities for Local Smart Energy Systems

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Keywords: Global, GIS, energy access, renewable energy, smart energy systems

Globally, two main central cases of future smart energy systems materialise. First, about 66% of humans will live cities in the year 2050, most of them in fast-growing cities with less than 1 million people. This will require significant focus on planning for sustainable energy infrastructures in developing urban areas. Second, in rural areas about one billion people lack electricity access. The 7th Global Sustainable Development Goal is to connect all humans to clean and affordable energy supply by 2030. Both cases combined may comprise the largest growing markets in the energy sector. However, there is little data available to assess future demands, the feasibility of supply systems, and the integration of renewable energy sources. To facilitate planning of smart energy systems globally, the present paper develops a global energy atlas. The aim is to map met and unmet demands, to delineate prospective supply areas and infrastructures, and to assign potentials of renewable energy sources to these. Remotely sensed data and their derivatives such as nightlights, population grids, land use, and renewable energy intensities are used in absence of ground data. The result is a model, which combines demand and supply under geographical constraints. A global 1km²- raster-based geographical information system platform is used to model quantities, to calculate generation costs, and to delineate prospective supply systems in the context of smart energy systems. The result is a quantitative planning framework, which will assist in modelling smart energy systems globally and provide the data basis for the provision of energy services, the development of district heating and cooling systems and the integration of renewable energy sources.

Kamal Kuriyan is a senior developer and research associate at the Department of Chemical Engineering, Imperial College London. His work focuses on the development of tools for the modelling and optimization of process and energy systems.

A combined spatial and technological model for planning district energy systems

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This paper describes a combined spatial and technological model for planning district energy systems. The model is formulated as a mixed integer linear program (MILP) and selects the optimal mix of technology types, sizes and fuels for local energy generation, combined with energy imports as required, and exports of any excess energy. The model can also be used to select the location for the energy source, the distribution route, and optionally, to select the heat loads that will be connected to a district energy system. The model is being developed as part of a planning application with a heat-map based user interface.

The spatial framework, which describes the location of energy demands, supply technologies and links for energy transport, can be obtained from a heat map. This information is processed into a network representation with nodes for each demand point (building), supply point or intersection, and arcs representing potential paths for connecting pipeline. The technological framework is based on the Resource Technology Network (RTN) representation (Samsatli and Samsatli, 2016). This has been used in a several applications for the planning of sustainable systems, and is a convenient representation for describing alternative pathways for energy generation, storage and consumption. RTNs for heat networks can incorporate a variety of supply technologies (e.g. heat pumps, boilers, combined heat and power units) and fuels (e.g. biomass, gas, electricity). Heat recovery from a user defined heat source may also be incorporated into the RTN. The RTN can also include technologies such as domestic boilers and heat pumps, so heat networks can be compared with alternatives based on gas or electric heating.

A mixed integer linear optimisation model is formulated which incorporates an energy balance for each node in the spatial framework. The model incorporates a resource balance for each supply or demand location *i*, and each set of time intervals *(t,tm)*, where *t* are minor periods representing seasonal or diurnal demand variations, and *tm* are major periods for investment decisions. The conservation equations span all possible technologies *r* for heat generation and consumption. In the equation below *RS* represents the resource surplus at a node, *P* is the operating rate of technology *j*, *μ(j,r)* is a coefficient that defines the production rate of resource *r* by technology *j*, *IM* and *EXP* are imports and exports, *Q* represents the flows between locations *i* and *i1*, and *D* represents the demands.

$$RS(r,i,t,tm) = \sum_j \mu(j,r)\, P(j,i,t,tm) + IM(r,i,t,tm) - EXP(r,i,t,tm) + \sum_{i1} Q(r,i1,i,t,tm) - \sum_{i1} Q(r,i,i1,t,tm) - D(r,i,t,tm)$$

$$OBJFN = \sum_{tm} \sum_m OBJWT(m,tm)\, VM(m,tm)$$

The model optimises an objective function that is the weighted sum of metrics *m* for investment costs, operating costs/revenues and emissions. Scenarios can be formed for varied emission targets, price levels for fuels and delivered heat or electricity, and with different fuels and technologies for heat generation. Results for scenarios based on a synthesised dataset will be presented.

Samsatli, S., Samsatli, N. J., (2015), A General Spatio-Temporal Model of Energy Systems with a Detailed Account of Transport and Storage, Computers and Chemical Engineering, 80, 155-176.

Joseph Maria Jebamalai is a PhD fellow at Ghent University, Belgium. Previously, he worked as a researcher on solar thermal power plants at Fraunhofer, Germany. He graduated with honors from KTH Royal Institute of Technology, Sweden, in Sustainable Energy Engineering. His area of interest includes district heating and cooling networks and thermal storage. He is currently involved in the HeatNet EU project.

An automated GIS-based planning and design tool for district heating: Scenarios for a Dutch city

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Keywords: district heating, automated GIS based planning tool, network dimensioning, cost estimation, scenario comparison

The design, dimensioning and cost estimation of a district heating (DH) network poses many challenges. Especially for large networks, producing a network layout manually is complex and time-consuming, and the integration of Geographical Information System (GIS) tools becomes very valuable. Several tools exist for hydraulic network calculations but require expert knowledge to use. Custom-made spreadsheets allow more or less automated hydraulic calculations and pipe selection but can be error-prone if not properly used and are not suitable for large networks. Moreover, there is usually no automatic feedback of the results to the GIS tool. And lastly, the cost estimation of the network deployment is also typically done with yet other spreadsheets. In short, the different design aspects typically require different software tools and the whole process is usually not well integrated. This makes the design process time consuming, in particular when different scenarios need to be recalculated for e.g. a feasibility study.

In this paper, we present the methodologies behind a novel software tool that provides solutions to the challenges stated above. The tool has been developed as a plug-in to a GIS tool and provides optimized and automated network routing algorithms, including all aspects of DH network dimensioning as required for a high level feasibility study. Results are immediately visualized in the GIS environment. Calculation of different scenarios is fast and straightforward with immediate feedback. The tool also supports budgeting and return on investment calculations.

A district of the city of Nijmegen is used as a case study to demonstrate the tool. The effect of different design parameters is investigated and several scenarios (of potential areas to be connected to the network) are explored. Use of the tool results in a drastic reduction of the DH network design time and it is scalable to even very large networks.

Jakob Zinck Thellufsen is an assistant professor at Aalborg University. He received his PhD degree from Aalborg University as well. He works with energy system analysis focusing on smart energy systems; how smart energy systems work in an interconnected Europe, and the impact of energy savings.

Geographical distribution of heat savings in a smart energy system

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In the transition towards 100% renewable energy systems, most research points to the importance of including energy savings to reach the most cost-efficient solutions. The building sector is a key target of energy savings, the reason being that in many countries, heating account for one third of the national energy demand. To reach the most cost-efficient future energy system, it is important to find the right balance between the cost for heat savings and the cost of heat production. The variation in building quality offer different potentials for savings in buildings, where different types of saving measures have different cost rates, resulting in some being cheaper than others. In future smart energy systems, where district heating will play an important role, the introduction of large amounts of renewables and utilization of waste heat in the district heating, result in potential inexpensive heat supply cost, while the more flexible units like combined power plants and boilers will be more expensive.
The balance between heat savings and heat production have been identified in several papers on an overall national level, however, what becomes apparent is that there is a geographical aspect that needs to be taken into account. The building mass is very different in urban areas with high-density population, apartment buildings, and offices, compared to rural areas and small villages. These differences also show up in the building quality, where some areas consist of new buildings while others predominantly consist of houses that are more than 50 years old. Furthermore, the heat supply costs also differ based on the geographical location of the buildings. In a smart energy system, urban housing in densely populated areas will be supplied by district heating, while heat pumps or biomass boilers will supply houses with individual heating. The geographic difference in heat supply and building types will affect the level at which energy savings will be economically feasible.
This study investigates how the geographical differences in heat supply and building types in a smart energy system influence the economic feasibility of investments in heat savings. This economic feasibility is found by using energy system analysis to identify marginal production costs and combining it with a geographical assessment of building types and heat demands to identify the different saving profiles for different areas. Together, this delivers a geographical assessment of saving potentials, where the economically feasible balance between costs and savings is identified. The study specifically applies the method to the case of Aalborg Municipality and the plan for a

Smart Energy Aalborg in 2050. Furthermore, the analysis examines the socio-economically best solutions, compares these to the current tariff structures and identifies if the structures helps to achieve the required energy savings for 2050.

Session 4: Low-temperature district heating grids

Carsten Bojesen is an associate professor and **Maksym Kotenko** is a PhD fellow at Aalborg University. The topic of their study is the optimization of low-temperature district heating. Currently, they work with drag reducing agents as one of the measures that can optimize district heating by saving pumping energy.

Friction Reducing Additives in the Future District Heating and Cooling Systems

Maksym Kotenko, PhD Fellow, Carsten Bojesen, Associate Professor (presenter), Mads P. Nielsen, Associate Professor
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Keywords: friction reducing additives, district heating and cooling

Additives that can reduce friction losses in flowing liquids are well known. Back in the 1980'es and 90'es a number of extensive studies of both lab and larger scale testing were carried out. However, despite of the proven impact the intended implementation in district heating grids was never realized. The main reasons for this were:

- The additives caused a corresponding reduction in the heat transfer, which particular was a problem in the shell & tube steam condensers on the large CHP plants.
- Secondly some environmental concern existed among the district heating companies
- Thirdly, one of the options for utilizing the friction reduction would be to increase the flow velocity. However, there were some concerns about the increasing risk of water hammering in the DH pipe system during valve operation.

The developments in the district heating supply sources, the extensions of supply area and the increased population densities in urban areas have actualized the interest for and the potential for friction reducing additives. Further, the potential benefit is even more pronounced in the future district cooling systems.

Recent experimental studies of new friction reducing additives confirm the findings from earlier work.

This presentation will summarize the early and the new experimental findings and evaluate the problems and benefits of using of friction reducing additives in district heating and cooling grids in the future.

A roadmap for the next steps followed by implementation of friction reducing additives is proposed.

Dirk Vanhoudt is senior researcher in the Energy Technology Unit of VITO. His main research topic is the development of next generation district heating grids. Apart from conducting scientific research, Dirk Vanhoudt also works as an energy consultant for companies. Dirk Vanhoudt is the technical coordinator of TEMPO.

Technological Solutions to Reduce District Heating Network Temperatures - the TEMPO Project

Dirk Vanhoudt[1, 2] *(presenter), MSc, Tijs Van Oevelen*[1, 2]*, PhD, Christian Johansson*[3]*, PhD, Johan Sjögren*[3]*, PhD*

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Keywords: digitalisation, temperature reduction, demonstration

The technical and economic viability of today's district heating (DH) networks are undermined by transitions to highly efficient building stocks and ineffective business models which fail to benefit all stakeholders. In TEMPO, a Horizon 2020 project started in October 2017, solutions to overcome these issues are implemented, through 1) innovations to create low temperature (LT) networks for increased network efficiency and integration options for renewable and residual heat sources; and 2) new business models to boost network competitiveness and attractiveness for stakeholder investment. In TEMPO, six innovations related to networks, digitization thereof and building optimization undergo final development (Technology Readiness Level 7-8).

The six innovations in the project are: 1) an automated on-line supervision platform to detect faults in DH substations; 2) visualisation tools for expert and non-expert users; 3) a smart network controller to maximize sustainable energy consumption and minimize the return temperature; 4) an innovative piping system; 5) building installation optimization; and 6) decentralised storage buffers.

The innovations are combined into three solution packages suitable for three different application areas. For each application area, a demonstrator was selected. Firstly, a new LT DH networks in urban areas, which, through lower network temperatures enables the integration of a geothermal energy source and cooling. Secondly, a new LT DH networks in rural areas for which the reduced temperatures open up the possibility to integrate a renewable energy source at a later stage. Finally, an existing (HT) networks whereby it is examined to which extend the temperature levels can be reduced through particular emphasis on end consumer engagement.

Each solution package is coupled to an innovative business model, which can leverage cost savings due to improved energy efficiency to offset the investment costs.

This paper will present an overview of the different technologies in the solutions package and describe how to apply them in line with the general work process in TEMPO. Furthermore, initial results of the project will be presented along with a road map for further development.

Igor Krupenski is the head of a heat and gas supply systems design company and a lecturer in the Department of Energy Technology, Tallinn University of Technology. He defended his PhD thesis in the Department of Thermal Engineering of Tallinn University of Technology in 2010. The topic of the doctoral thesis was 2-phase flows in oil-shale CFB boilers. Igor Krupenski is involved in projects related to district heating and gas development in Estonia, including the Baltic connector gas pipeline (Estonia – Finland interconnection).

Development prospects for small low-temperature district heating networks

Igor Krupenski[1,2]*(presenter), Anna Volkova*[1]*, Henrik Pieper*[3]*, Eduard Latõšov*[1] *, Andres Siirde*[1]
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Keywords: LTDH, small district heating networks, 4GDH, heat pumps, seawater thermal energy

Low-temperature district heating networks have many advantages, including low heat loss and ability to utilise renewable energy sources, and to integrate large-scale heat pumps. One of the main obstacles to the implementation of low-temperature district heating is the existing infrastructure along with consumer heating devices that were usually designed to operate at high temperatures, often up to 80°C. If a district heating network is installed for a new urban area, these obstacles can be avoided by constructing low-energy buildings, which have floor heating installed.
The developer of the new urban area has a variety of buildings heat supply options: connection to the existing district heating network, as well as the small local district heating network installation, individual heating solutions, integration of renewable energy sources, such as seawater and solar heat, etc.
The study presents an analysis for the alternative heat supply scenarios of the newly developing city sub district of Kopli (Tallinn, Estonia). The development of the sub district of Kopli includes 2 stages. Within the first stage of the development, it is planned that there will be 21 multi-family residential buildings with underfloor heating and the total heat demand of 1,2 MW. Within the second stage of the development, it is planned that there will be 49 multi-family residential buildings and 4 public buildings with the total heat demand of 5,3 MW. The following scenarios were analysed for both stages of the development from technical, economic and environmental points of view: connection to the existing district heating network (supply-return temperatures 95/55°C, gas-fired boiler house); small local low-temperature district heating network installation(supply-return temperature 60/35°C, small gas-fired boiler house); small local low-temperature district heating network installation (supply-return temperature 60/35°C, small biomethan gas-fired boiler house, integrated large-scale heat pump for seawater as heat source).

Tobias Sommer is a physicist and received his PhD with honors from ETH Zurich, Switzerland. Since 2017, he is the project manager of the NODES-Lab, a district heating network at a lab scale. He is interested in physical processes in fluids, such as mixing in lakes or cafe latte, hydraulics in thermal networks and wind-wave interactions in the ocean for windsurfing.

Lowering the pressure in district heating and cooling networks by alternating the connection of the expansion vessel

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Keywords: low temperature networks, district heating and cooling, pressure reduction, expansion vessel

Piping costs are a major fraction of the initial investments for district heating and cooling networks and limit the dissemination of such networks. In this work, we present a new method for reducing the maximum pressure in such systems. Reducing the maximum pressure decreases the wall thickness for piping and thus decreases investments.
We focus on district heating and cooling networks of extremely low temperature below 20 °C. Such systems are nowadays widely spread in Switzerland. At such low temperatures, direct cooling (without a chiller) is possible and low temperature environmental heat or waste heat from industrial processes serve as energy sources. For heating purposes, heat pumps are required to raise the temperature level.
Low temperature heating and cooling networks typically consist of a warm line (with e.g. 10 °C) and a cold line (with e.g. 6 °C). The clients are equipped with distributed circulation pumps and draw water from one of the two lines, depending on heating or cooling demand. Seasonal storages (typically passive without circulation pumps) close the mass and energy balance. Distributed circulation pumps cause complex hydraulic dynamics that are difficult to predict and may result in cavitation at the circulation pumps, if the suction side pressures are below the evaporation pressure. To avoid cavitation, large system pressures are required. Large pressures require costly piping with thicker wall thicknesses.
Our method guarantees save operation for all operational states at the lowest feasible pressure. This is achieved by alternating the connection of the expansion vessel depending on the pressure dynamics in the system. Alternating the connection of the expansion vessel is, in contrast to a fixed connection point of the expansion vessel, a new approach in hydraulic systems. We first introduce our concept theoretically, then validate it in a laboratory setting (Fig. 1) and finally apply it to monitoring data of an existing large-scale low-temperature network located at ETH Zurich, Switzerland. For the implementation of the method, we present a new mechanical, self-operating valve.


Fig. 1: NODES Lab, a district heating and cooling network at laboratory scale.

Marco Pellegrini, born in 1981, graduated in Mechanical Engineering in 2006, received his PhD in Engineering of Machines and Energetic Systems in 2012, and is now junior researcher at the Industrial Engineering Department of University of Bologna. He is the author of 52 papers in international journals and conferences about renewable energies and, more in general, industrial mechanical plants. Marco Pellegrini is the coordinator of the iEnergyDistrict project.

Technological and non-technological barriers in the revamping of traditional district heating networks into low temperature district heating: an Italian case study

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Keywords: low temperature district heating; revamping; case study; analytic hierarchy process.

The revamping of existing high temperature district heating systems with low temperature solutions will ensure a better usage of primary energy thanks to the reduction of thermal losses through the networks and to the possibility of use low-grade enthalpy heat for the scope, including renewables. However, several criticalities are present that make the evolution from the 3rd to the 4th generation of district heating not immediate.
First of all, technical limitations should be analysed: the main challenge in reducing the supply temperature is the respect of thermal supply specification. A second issue involves techno-economic concerns, since modifications to the existing infrastructures (energy production plant, energy supply grid, end-user substations up-grade) may be necessary. A third relevant aspect includes all the problems connected with monitoring and automatic control of energy fluxes, in particular in smart low temperature district heating with decentralised energy production. Furthermore, also non-technological barriers should be faced, including relationship with the local institutions, policy makers and stakeholders, authorization and normative issues, as well as contractual limitations and constraints with energy supply end-users.
Therefore, district heating operators would face several variables in the implementation of low temperature district heating, depending on specific operative conditions, customers' contract of supply, environmental and normative boundary condition. Furthermore, all of these variables may be very specific for each application, thus making very complex the evaluation of how to implement an existing district heating network moving towards a 4th generation network.
The paper aims to identify general technological and non-technological barriers in the revamping of traditional district heating networks into low temperature ones. Possible solutions are suggested, including also relevant advices for decision makers. Furthermore, the paper shows a case study in Italy, and analyses how the possible

solutions required for the up-grade of the existing district heating network can be classified through the Analytic Hierarchy Process (AHP) to prioritize the best resulting ones for more advanced evaluations.

Session 5: Low-temperature district heating and buildings

Jan Eric Thorsen holds a MSc in mechanical and energy related engineering and is the director of Danfoss Heating Segment Application Centre. His main focus is on positioning the District heating Technology in the future energy system. Jan Eric Thorsen has performed consultant work in regard to district heating and cooling systems. He has participated in a number of governmentally funded projects on Low-Temperature District Heating, EnergyLabNordhavn and 4th Generation District Heating in which a number of papers have been published.

Load shift experience with ULTDH Booster Substation for multifamily building

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Keywords: heat booster station, ultra-low temperature district heating, load shift, heat pump, 4th generation district heating

In this presentation, we present the first field experiences related to load shift potential of an ultra-low temperature district heating (ULTDH) consumer unit for multi-family houses with an integrated heat pump for domestic hot water preparation and domestic hot water circulation. We describe the applied system, as part of the EnergyLabNordhavn project.
The presented concept opens the opportunity for load shift related to domestic hot water production. The presentation describes the experience and quantifies the flexibility potential. Utilising the flexibilities, e.g. load shift potential, on the building side, can become an important part of optimising the operation of the district heating network. Besides this, to achieve the goal of 100 % renewable (RE) heat and power supply, increased energy efficiency and utilisation of available RE resources are important. In this context, the benefits of ULTDH are multiple. First, heat losses from the district heating network can be reduced, which also becomes increasingly important in the future heat supply to low energy buildings. Second, ULTDH improves and enables the use of low temperature renewable energy resources such as solar, geothermal, industrial waste heat and increase in efficiency of central heat pumps. Moreover, ULTDH in local networks opens for possibility to connect new users to existing DH systems without large additional capacity investments.

Christian Holmstedt Hansen is an economist with a strong interest in the energy sector and in particular district heating. His work mainly consists of energy system modelling and analysis regarding the competitiveness of district heating.

Cost efficiency of district heating for low energy buildings of the future

Christian Holmstedt Hansen[1] *(presenter), Oddgeir Gudmundsson*[2] *and Nina Detlefsen*[1]
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Keywords: district heating; low energy buildings; cost efficient; renewables

In the recent years, the success of the Nordic district heating systems to phase out fossil fuels and provide green and sustainable heat has been more and more recognized around the world. Projects like the 4DH research platform and Heat Roadmap Europe have successfully communicated that district heating is the only viable solution to efficiently utilize both low-grade renewable energy, excess heat from other sources as well as waste heat for providing heat for space heating and domestic hot water purposes. Nevertheless, there are open questions regarding cost competitiveness of district heating in combination with low energy buildings of the future. In fact, one of the challenges district heating is facing, is the general perception that district heating is too investment intensive compared to individual solutions. In many cases, that perception is also used to imply that district heating has no future with the introduction of strict building energy codes that require new buildings to fulfil low energy buildings standards. In this paper, the levelized cost heating using district heating and individual heating solutions are compared by looking at an area where both the heat demand per square meter as well as the distance between buildings are varied. The space heating and domestic hot water demand is varied from 106 kWh/m^2, which is comparable to typical Danish building from 1970, down to 37,6 kWh/m^2, which is comparable to passive house, or near zero energy building. The results show that even with nearly zero energy buildings district heating systems remain very competitive in both inner and outer city areas.

Biographical Note(s):
The authors main in research is in district heating and its role in energy systems

Kevin Michael Smith is a researcher at the Technical University of Denmark (DTU). His research is focused on model-based control of floor heating systems and heat-booster substations for ultra-low temperature district heating networks as well as demand-control of decentralised ventilation for renovated apartment buildings. He completed his PhD and Master at DTU and his Bachelor of Applied Science at the University of Toronto.

Model predictive control of a heat-booster substation in ultra-low temperature district heating networks

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Keywords: MPC, heat booster substation, 4th generation district heating, heat pumps, domestic hot water

Copenhagen is currently adding a new urban district that will accommodate 40,000 residents and an equal number of workplaces. The district of Nordhavn has received the highest certification for sustainability by the German Sustainable Building Council, and its development will focus on holistic sustainable solutions, including demonstration projects for low and ultra-low temperature district heating (ULTDH). This infrastructure will motivate a fourth generation of district heating in which smart thermal grids accommodate renewable energy sources and low-energy buildings while maximising distribution efficiency. The lower network temperatures allow greater utilisation of low-exergy heat sources, such as solar radiation, ground-source heat exchange, and waste/surplus heat from industrial processes. Meanwhile, the lower temperature differences between the ground and network will reduce heat losses during storage and transmission. Together these measures will improve the sustainability and security of supply in future energy systems. The area of Nordhavn will be used to develop and demonstrate new solutions for district heating. This includes local heat stations, ultra- and low-temperature distribution networks, and various scales of heat storage. The infrastructure will require communication, data structures, forecasts, and a common-sense approach to avoid peak loads and allow greater shares of renewable energy sources (RES) in the supply mix. In these new distributed systems, all users will need to plan and communicate, and incentives will reward the most flexible users for local grid stabilization. Such flexibility could include passive or active thermal storage as well as energy conversion from electricity to heating or cooling where appropriate. The incentives could include variable pricing schemes for electricity and heating.

The district heating network in Nordhavn currently operates with 70 °C supply temperature and approximately 40 °C return temperature. The key concept in 4th generation district heating is a shift towards lower supply and return temperatures. A key advancement would utilise of 40 °C supply temperatures with supplementary heating for production of domestic hot water (DHW), which requires at least 45 °C for direct consumption and at least 55 °C in storage. However, the grid must ensure adequate heat supply to every user, which prohibits a reduction in supply temperatures until all users can meet their needs with the lower temperatures. This removes any early incentive for individual users to install new technologies capable of utilising ULTDH. As such, the system could allow full or partial tapping from the return line of the district heating network. This would negate the need for a full transition and could enable distributed heat production in the network. In such a system, the heating price and temperature in the return line could vary locally. The electricity price would also vary, so the user could tap the return line and optimally use electricity for the production of domestic hot water. The use of a heat pump could minimise electrical input, and thermal storage could exploit variable RES and shift peak demand for DHW. The combination of heat pump and storage tank in a ULTDH network may be a called a heat-booster substation. The EnergyLab Nordhavn project will demonstrate one such substation in an apartment building in Nordhavn, and this paper sought to determine the optimal charging time of its tank at various boundary conditions.

The authors modelled the heat-booster substation using the equation-based Modelica language in Dymola and existing components from the Modelica Buildings Library 4.0. This version of the library is also compatible with the open-source platform JModelica, which is well suited for optimisation problems. Actual performance data from static tests served as input for individual component models of the heat pump, heat exchanger and thermal storage tank. Dynamic data from a laboratory test-setup validated the complete system model. Historical data fed a prediction model for the tapping of DHW at the demonstration site. The simulations determined the optimal charging with different pricing schemes for heating and electricity. The investigation analysed the sensitivity of results to changes in tapping profiles and temperatures from the district heating return line. Based on the results of this study, the authors hope to demonstrate the method with online model predictive control of a real heat-booster substation in Nordhavn in the near future.

Pierre J.C. Vogler-Finck has a background in energy engineering and control, with an industrial PhD in forecast and control of heating loads in buildings from Aalborg University in Denmark. His research and development work at Neogrid Technologies focus on data driven modelling and control of heating in buildings, aiming at improving the efficiency of operation and the integration within the broader energy systems.

Reducing supply temperature in existing buildings with an innovative advanced heating curve control technology

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Keywords: supply temperature reduction, control technology, building heating operation.

Reducing the supply temperature to the necessary levels is an essential step in the improvement of operation of district heating systems. An important dimension of this process is the identification of the minimum temperature required to ensure thermal comfort in the building stock within the system.

Here, an innovative supply temperature control technology for buildings is presented: PreHEAT. This controller computes the lowest possible supply temperature allowing to maintain a given level of comfort in given conditions, based upon statistical learning of the building's thermal characteristics and various weather parameters. At the same time, the controller provides a dynamic short-term forecast of the heat load, which can provide further value in optimisation of district heating operation.

The control was tested in a number of buildings in Denmark, including single family houses, large residential buildings, and a school. Results show a large potential for decreasing the supply temperature in the existing buildings considered, with reductions as high as 10°C or more compared to existing weather compensation solutions. Moreover, neglected operational issues were often uncovered in the process of deploying and tuning the controller, which highlights the potential value of the solution for condition monitoring of the building and its heating system.

Jens Møller Andersen holds a MSc in Energy Technology and works as a senior consultant at Energysolution.

Lowering of return temperature in district heating systems by Integration between heating and ventilation systems in households

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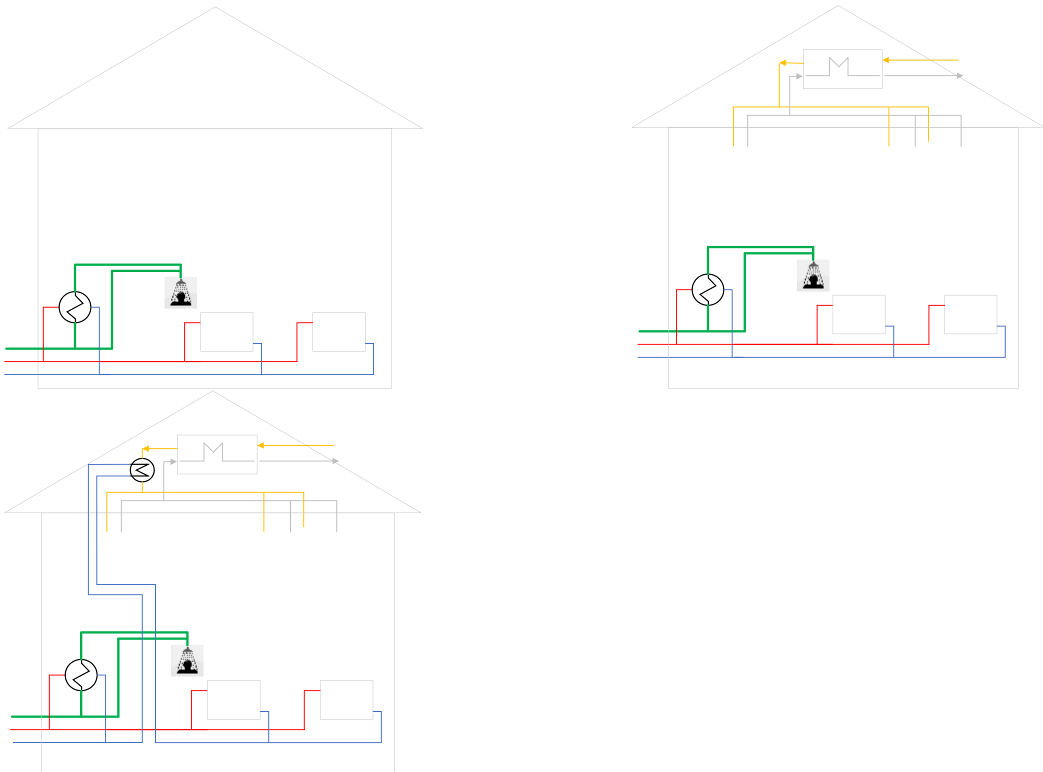
Keywords: low temperature district heating, heating and ventilation integration

The return temperature is one among few parameters that governs both the capacity and the efficiency of a district heating system. This paper shows how to reduce the return temperature in a district heating system.
Integration between heating and ventilation systems in households may create benefits and compensate for shortcomings and poor control of district heating installations. This article describes how and quantifies the benefits of integrating the ventilation system to the heating system. The way to do it is both simple and cheap to add to both new and existing systems. By the integration there is obtained:

- Better comfort
- Lower district heating return temperature
- It may result in lower heating prices if there is an incentive structure in the district heating system
- Gives higher capacity and lower pump costs in the district heating system
- May cause fewer cases of "short circuit" of differential pressure.
- Allows district heating customers who have trouble getting enough heat to get better conditions.
- Compensate for non-sufficient radiator or floor heating system
- Compensate for incorrectly settings in heating system

Most private houses do not have a ventilation system. In Denmark, it has only been a requirement for ventilation in new built houses since 2010. Therefore, the most houses are without ventilation system. Even though many houses are being renovated, only few install ventilation systems. But more than 60% of the households in Denmark have district heating. This gives good possibilities for integration in the existing buildings.
The figure shows a flow scheme is of how to integrate ventilation and district heating in a simple and efficient way



With DH With DH and Ventilation With integrated DH and ventilation

The fact that ventilation systems are a relatively new type of technical installation in houses is probably the primary reason why the possibilities offered by integration with district heating systems have not been investigated and used.
The preliminary calculation shows a reduction of district heating return temperature of 9°C in peak load situations; in low temperature district heating system that today have a return temperature of 30°C.

Session 6: Organisation, Ownership and Institutions

Gijsbert Korevaar holds a MSc in Chemical Engineering and a PhD in the field of sustainable chemical process and product design from Delft University of Technology. His research focuses on the design and analysis of sustainable industrial-urban clusters, strongly related to Industrial Ecology and Industrial Symbiosis. His field of expertise includes system analysis, process modelling, life cycle assessment, circular economy, and design methodologies. Gijsbert Korevaar has been involved in several national and international projects and is the chair of the education committee of the Delft-Leiden MSc programme on Industrial Ecology.

Agent-based modelling for the thermal energy transition of natural gas dependent neighbourhoods

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Keywords: thermal energy systems, built environment, energy transition, natural gas, agent-based modelling, socio-technical systems, complex adapting systems.

A large share of space heating in the Netherlands is supplied by means of natural gas. To achieve the European Union's objectives to reduce greenhouse gas emissions to 80% by 2050 through domestic reductions alone, a thermal energy transition of the country's heating and cooling sector is required. Our research aims at supporting this transition by exploring pathways through which neighbourhoods that currently rely on natural gas for space heating can transition towards a natural gas free future.
We address the challenge of transitioning towards natural gas free heating in neighbourhoods by means of an agent-based modelling process, based on the perspectives of socio-technical and complex adaptive systems. Through the lenses of socio-technical systems, we account for technology, actors, institutions and their interrelation. Similarly, by adopting the perspective of complex socio-technical systems, we consider the heterogeneity of actors and their individual behaviour, along with other socio-technical components, which together may enable learning, adaptation, collective-behaviour, self-organization and led to the transformation of the neighbourhood. Using agent-based modelling allows us to study the systems' performance and evolution, and to explore policies that might yield the desired outcomes at a neighbourhood level. The modelling process involves collaboration with potential users through case studies.
Different applications can be derived from our research. First, outcomes can be used to explore how neighbourhoods in the Netherlands can transition towards natural gas free heating. We will shed light on possible developments over the coming years and

possible policy measures. Second, results can be used to discuss with stakeholders possible action points and research plans.

Søren Djørup is an assistant professor in Energy Planning at Aalborg University. His research focuses on economic and regulatory aspects of the transition to a renewable energy system.

The Technical Rate of Substitution between Wind Power and Photovoltaics in a Smart Energy System

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Keywords: electricity market design, technical rate of substitution, wind power, photovoltaics, smart energy systems

The build-up of renewable energy capacities in the electricity system has historically been promoted through feed-in tariffs and other schemes supplementing wholesale electricity markets. The majority of these has been technology specific and directed towards prioritised technologies, for example dedicated tariff payments to e.g. wind power or photovoltaics.

Lately, the idea of ’technology neutral’ tenders has been promoted as a policy measure to enable competition between different renewables. The motivation for introducing competition is to stimulate economic efficiency. From an economic perspective, the idea of introducing competition between renewable technologies head-to-head must be based on the unspoken assumption of technologies being perfect substitutes. It is immediately clear, however, that technologies relying on weather patterns to some extent must be heterogeneous by nature. Indeed, the question of production distribution data is also recognised as an important issue in technical system analysis of renewable energy system based on variable renewable energy sources (VRES).

The question is then how these given conditions of heterogeneity affects the efficiency of the aforementioned ‘technology neutral’ market designs. What is the substitutability between the technologies? How severe is the heterogeneity for the efficiency of the market designs?

In economic terms, the technical rate of substitution (TRS) describes the substitutability. To uncover this rate is a precondition for proper market design and analysis. When assessing the TRS between variable renewable energy sources, it is important to do it in a holistic system perspective that includes not only the electricity sector but also heat, gas, and transport sectors. A lot of research has shown large synergies from integrating different energy sectors when VRES capacity is expanded. The TRS must therefore be estimated through a Smart Energy System approach.

The purpose of this paper is to uncover the technical rate of substitution between wind power and photovoltaics in a holistic energy system perspective. The TRS will be derived in a 100% renewable energy system. The outcome of this research will provide a basis for assessing the effect of specific tender designs on the total energy system costs.

Niels M. Westera is an industrial ecologist with particular interest in organisatory or regulatory solutions to enhance the functioning of sociotechnical systems. His expertise lies within the social impact of alternatives to natural gas for heat provision in the Netherlands.

Exploring community acceptance of ownership models for district heating as an alternative to natural gas-based residential heating in a city in the Netherlands

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Keywords: ownership, district heating, heat transition, phase-out natural gas, community acceptance, distributive justice, procedural justice, trust.

Possessing the largest natural gas reserve in Western Europe, the Netherlands relies on this resource. Most households depend on natural gas for heat provision, accounting for 51% of its consumption. Social problems with earthquakes related to natural gas exploitation and the need to reduce greenhouse gas emissions challenge the country to find alternatives. While district heating exists in some areas and is being considered for others, downsides (e.g. challenges of organizing collectiveness, monopolism, dependency and localism) limit its community acceptance –defined as a product of procedural justice, distributive justice and trust (Wüstenhagen, Wolsink, & Burer, 2007). Different types of ownership of district heating networks (e.g. private, public, cooperative) may offer opportunities to overcome or manage some of these downsides and increase community acceptance.

The objective of this work is to explore community acceptance of different forms of ownership of a potential district heating network expansion in Utrecht, a city in the Netherlands where space heating in some neighbourhood's is based on natural gas. We propose a design space to describe ownership models in district heating networks, based on desk research and experts interviews. We used our design space to conduct an online survey to explore community acceptance within residents (N=198). The sample's representativeness is limited by respondents having higher education level than the average Utrecht population and a lower percentage of respondents living in social housing (-32%).

We found indication that most respondents appreciate the role of public bodies (e.g. public electricity grid operators and municipalities). Findings also suggest that network activities (NA) are the most suited for public ownership. Energy companies were most selected (30%) for the ownership of the generation activities (GA). While community-owned heat cooperatives offer opportunities to enhance distributive justice, this model was selected fewer times (GA=25%, NA=22%). In terms of procedural justice, we expected respondents to indicate a wish to be informed about the changes in their heat provision situation (Langer, Decker, & Menrad, 2017). Instead, the majority of respondents wanted to have the right to consent (47%). A moderate relation was also found with house ownership: being a house owner increased the level of participation. Financial participation by becoming shareholder was preferred by a minority of respondents (10%), as found by Langer et al. (2017). This seems to be unrelated to the willingness to invest, as more than 30% was willing to invest upfront in connection fees or heat cooperatives. Municipalities and grid operators were often indicated as trusted organizations, with smaller numbers for energy companies and neighbourhood organizations. Answers revealed a slightly higher acceptance for public bodies owning parts of the district heating value chain and a preference to be able to consent to the deployment of technology.

While suitable ownership models are context dependent, we demonstrate how our proposed design space can be used to research these models and envision promising research lines for this research's case study. Further social research is needed to explore how procedural justice, distributive justice and trust are interrelated and result in the actual implementation and long term satisfaction of the district heating technology.

Daniel Møller Sneum is a former analyst in IEA, Green Energy and PlanEnergi and now conducts his PhD studies within the Energy Economics and Regulation Group in DTU Management Engineering. His research focus is on the flexibility of district heating and cooling in the energy system, and how this is facilitated through markets and regulation.

State of the art in the States: Applying an analytic framework for flexibility in US district energy systems

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Keywords: heating and cooling, regulation, policy evaluation, smart energy systems, methodology, USA

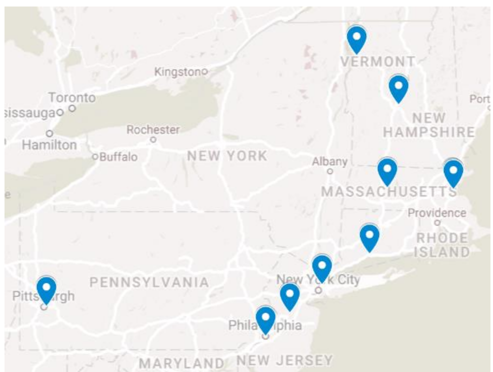
Introduction

Benefits of flexible coupling of heating and electricity sectors have been abundantly demonstrated in literature and real life. Such benefits include the increased ability to integrate variable renewable energy, and more efficient electricity markets. Barriers within regulation, physical conditions or policy for such coupling can mean that these benefits are not realised.

In the north-eastern United States (US), district energy systems are deployed but not necessarily flexibly integrated with the surrounding energy system. Among US district energy systems, universities are strongly represented. Additionally, the rather homogeneous organisation of the university systems along with their siting in different states with varying policy and regulatory conditions makes them well suited for a comparative study of barriers for flexibility. Thus, we ask,

1. How can a qualitative analytic framework for evaluation of policy and regulation for flexible district energy systems be designed?
2. Which policy and regulatory changes could be introduced for university district energy systems, according to the applied qualitative framework?

Methodology



We propose an analytic framework on flexibility-promoting policy and regulation, based on principles identified in existing literature. This initial design is completed in an iterative approach, by adding issues identified in semi-structured interviews with plant managers of ten different university district energy systems in seven different states (Connecticut, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Vermont), two regional transmission operators and several experts from academia and industry. Thereby, barriers emerging from the interviews are subsequently added to complete the framework. The revised analytic framework is applied in the review of each university, to obtain uniform and comparable results. Map shows placement of reviewed universities.

Results

Results are threefold. First, an analytic framework for evaluation of flexibility-conditions in district is developed. Second, the concrete results of applying the analytic framework on US district energy systems are applicable in regulatory, policy and institutional change regarding the role of district energy systems in integration of renewables and efficient electricity markets. Third, the real-world test of the analytic framework provides insight into its shortcomings and strengths.

David G. Barns is a PhD fellow in the Engineering and Physical Sciences Research Council Doctoral Training Partnership at the University of Leeds. His PhD explores the role of thermal storage in the decarbonisation of urban energy systems and is aligned to the EPSRC-funded Consortium for Modelling and Analysis of Decentralised Energy Storage.

The value(s) of thermal storage

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Keywords: Business models, local infrastructure, thermal storage, low carbon heat, policy

Heating, cooling, electricity, transport and waste systems can support each other to reduce carbon emissions (Mancarella 2014), and local heat storage infrastructure has a vital role to play in the transition to a sustainable, secure and cost-effective energy system (Lund *et al.* 2014). The deployment of thermal energy storage in the UK has been slow to date, and little is known about where and how systems are being used as part the transition to a smart energy system.

Traditional methods of valuing infrastructure investments and the business models needed to deliver them have tended to prioritise marginal economic gains over wider social and environmental values. Decisions made on this basis lack a recognition of the complex and interconnected nature of infrastructure systems and also that low carbon infrastructure can have benefits which extend well beyond climate change mitigation. This has contributed to the lock-in of high-carbon energy infrastructure.

Considering thermal storage projects as examples of local energy infrastructure, this paper applies the 'extended infrastructure business model canvas' (Foxon *et al.* 2015) to a range of schemes from the United Kingdom to consider how they deliver benefits and capture value. This includes an analysis of the types of business models being used, the impact of national and local infrastructure priorities, and the extent to which social, ecological, economic development, and fiscal value streams are sought. An extensive dataset on thermal storage projects from the UK has been collected and analysed through thematic analysis of non-traditional value streams. Classification of projects through a range of attributes, types of local actor involved, and interactions with other urban systems is used to investigate the role that thermal energy storage is playing in energy system transition in the UK.

The research finds that low carbon heating and thermal storage can act as an asset to the energy system when combined with business models, which value flexibility. The results also show an important role for local actors, especially municipal authorities, in driving forward innovative schemes, which seek to capture the widest range of values. There is evidence that the ongoing devolution of powers from central to local government, which is transferring responsibility for local infrastructure to the hands of devolved governments, municipal authorities and city regions, is playing an increasingly important role in the delivery of sustainable infrastructure. Of the ownership models identified, municipal-led and others with a social remit seek to capture the widest range of non-traditional benefits and pursue a broad definition of fiscal value beyond traditional notions of return on investment to include direct savings for end-users. Ownership model is also found to have an impact on whether local projects support national infrastructure priorities.

The paper makes policy recommendations that thermal energy storage is appreciated as an asset, which supports the energy system and highlights that it can also deliver a range of social, environmental and economic benefits that should be recognised in appraising future schemes.

FOXON, T. J., C. S. E. BALE, J. BUSCH, R. BUSH, S. HALL and K. ROELICH. 2015. Low carbon infrastructure investment: extending business models for sustainability. *Infrastructure Complexity,* 2(1), p4.

LUND, H., S. WERNER, R. WILTSHIRE, S. SVENDSEN, J. E. THORSEN, F. HVELPLUND and B. V. MATHIESEN. 2014. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy,* 68(Supplement C), pp.1-11.

MANCARELLA, P. 2014. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy,* 65(Supplement C), pp.1-17.

Session 7: Smart Energy Systems

Daniel Trier is head of department at PlanEnergi's office in Copenhagen and has a main focus on international collaboration projects to facilitate the transition towards energy systems based on renewable energy.

Sector coupling and distributed energy storages for the integration of renewable energy sources

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Keywords: energy storage, power-to-heat, power-to-gas, renewable energy, sector coupling

The transition to a low-carbon emitting energy system with a very high penetration of fluctuating renewable energy sources can lead to new challenges in balancing energy supply and demand. In this work, carried out within Annex 28 of the IEA ECES technology collaboration programme, the technical and economic potential for using distributed energy storages (DES) to integrate large amounts of fluctuating renewable energy sources (RES) in the future energy system has been investigated. The potential of integrating fluctuating RES by sector coupling (power-to-heat and power-to-gas technologies) has also been investigated for comparison with and in combination with the DES technologies.

The energy system simulation tool EnergyPLAN has been used for modelling various electrical and thermal DES technologies, as well as sector coupling technologies, in the context of a whole energy system on a national scale. A large number of scenarios with different energy system typologies and varying amounts of fluctuating RES penetration have been included in the analyses. Scenarios with other methods of balancing energy supply and demand, such as international electricity interconnectors and demand-side management have also been included for comparison. Three performance indicators have been used for quantifying and comparing the results; the annual socio-economic energy system costs, the annual system CO_2 emissions and an indicator for measuring the ability for integrating fluctuating RES in the system.

The results show that sector coupling together with an intelligent choice of DES technologies can enable the integration of large shares of fluctuating renewable energy in an energy efficient and cost-effective way. The best choice of DES and sector coupling technologies depends highly on the energy system context and must be analysed based on the total benefits for the energy system as a whole. In general, the most feasible scenarios are those that provide flexibility both in the electricity sector and the heating sector and have a link between the two in the form of heat pumps. Electrical DES technologies and power-to-gas technologies are generally technically feasible but must come down in price to be socio-economically feasible. The analyses furthermore indicate that a system redesign towards more low-carbon based district heating and more electric vehicles (preferably with smart charging) would further increase the technical and socio-economic feasibility of using DES and sector coupling to integrate high shares of fluctuating RES.

Jan Hennessy received a MSc in 2014, following almost two decades as a software engineer. Subsequently, working for Svebio and conducting research for the University of Gävle, Jay Hennessy joined the RISE Research Institutes of Sweden in 2016 as an Industrial PhD fellow. His PhD thesis focuses on future uses of thermal grids through interactions with the electricity grid and other energy networks.

Thermal grid flexibility: a review of district heating thermal storage to facilitate flexibility

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Keywords: smart thermal grids, flexibility, thermal storage, power-to-heat, heat-to-power

This work presents a review of literature that consider the storage capacity of thermal grids, in order to answer the question: how is the storage capacity of thermal grids used in system flexibility?
Variability and uncertainty of renewable energy sources (RES) can lead to high-cost curtailment of renewable generation and deployment of expensive, fast-start generating units. The use of storage devices to mitigate uncertainty and variability has been identified as particularly valuable.
The use of power to heat in thermal grids is well-proven and the national potential of various countries has been calculated in the literature. Recent work has also indicated under what techno-economic conditions the conversion of heat to power may be viable for use in district heating, potentially closing the conversion loop from power to heat to power. Using such conversion processes to provide electrical supply- and load-shifting flexibility also implies the need for thermal storage.
Thermal grids have been shown to facilitate the penetration of renewable sources such as wind and solar photovoltaics, either through continuous balancing of heat supply and demand, or through the use of thermal storage in sensible heat storage tanks and the inherent storage capacity of the distribution network pipes.
The potential for storage in the distribution pipes has been estimated to be in the order of several gigawatt hours in large networks. As the need for flexibility increases following the penetration of RES, it becomes increasingly important to quantify and take account of the storage capacity and limitations of both the thermal storage and the distribution pipes.

Shalika Walker is a PhD candidate from TU/e, the Netherlands. Currently, she is involved in the project "long-term infrastructure planning for the built environment" and analyzing the influence of clean energy initiatives on existing buildings. She has completed her Bachelor degree from Sri Lanka and her master studies from the KU Leuven, Belgium and INP Grenoble, France.

Gas-free alternatives for existing buildings with the use of heat pumps and thermal storage – a case study

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Keywords: heating, buildings, heat pump, thermal storage, optimal operation, uncertainty analysis

Distributed energy systems are gaining attraction within buildings and neighborhoods around the world along with energy transition. Within Europe and specifically in the Netherlands, the alteration to a gas-free greener energy infrastructure necessitates intense modifications of existing energy systems inside and outside buildings. On a positive point, the energy transition is happening when most of the major existing infrastructural gas networks are reaching the end of their lifetime. Therefore, this should be seen as an opportunity to modify the existing energy systems in an optimal manner. However, these modifications should be carried out with a clear estimation and understanding about the future changes in demands and urban structures. Therefore, it is a prerequisite to analyzing different infrastructure development scenarios for a particular neighborhood with uncertainties before planning major infrastructural changes.

The main energy consumption aspects of buildings are classified into heating, cooling and electricity, where currently heating needs a significant amount of fossil fuels. To reduce this fossil fuel utilization, heat pumps could provide one viable energy transition option. The associated lower CO_2 emissions make heat pumps an attractive option, which could play a promising role at the level of individual households, buildings, and neighborhoods. As part of a broader research on analyzing long-term infrastructure development scenarios, this paper provides one possible transition option with heat pumps and sensible water-based thermal storage system applied to an existing building in order to completely discontinue the gas consumption. The knowledge provided by current literature on the progress and uncertainty assessment of gas-free infrastructural developments is relatively low. This is because the actual cases where gas consumption is completely discontinued is relatively hard to discover. In the Netherlands, currently, 90% of the households are connected to the gas grid. An enormous effort is needed from all the decision maker parties (Policymakers,

consultants, house owner) to make real such a gas-free transition. Different decision makers expect dissimilar benefits. Getting all the parties to be on the same understanding is quite a challenge.
In this notion, this paper analyzes a transition scenario using heat pumps and sensible water-based thermal storage system applied to an office building in the Netherlands. The case study compares the transition scenario with the current situation. An uncertainty assessment has been done in order to recognize the deviation of the results with different uncertain parameters. The uncertainty of the transition scenario is evaluated with three different parameters categorized under technical, economic and environmental.

Tommy Rosén is a PhD fellow with a MSc degree in Engineering and with an industrial background from the steam turbine industry. His research is conducted at the division of Energy Systems at Linköping University and concerns improvements in district heating and steam turbine plants and enhanced system integration for better energy efficiency.

System perspective on biogas use for transport and electricity production

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Keywords: district heating, system perspective, electric buses, biogas, smart energy systems

In the ongoing process of moving towards a more energy efficient society, that reduces its CO_2 emissions and lower its use of fossil fuels, biogas and district heating can play an important role in the regional energy systems.
Linköping municipality has since 1997 managed biogas driven buses in the regional transport system and from 2015 all buses in the municipality are driven by biogas. Biogas is a renewable fuel and by replacing fossil fuels it can help to lower net CO_2 emissions. However, Internal Combustion Engines (ICE) in buses, using biogas or fossil fuels, still has a rather low efficiency in the range of 15-30 %. Much of the energy content in the fuel will be emitted as heat through the exhaust pipe. If the combustion of biogas instead takes place in a combined cycle gas turbine connected to the district heating system (DHS) this heat can be used for heating purposes. This could be a feasible solution if the transport system instead used electric buses charged with electricity generated by the combined cycle gas turbine.
This article has a top-down perspective on the regional transport system and the regional district heating system (DHS) in Linköping municipality. Two alternative systems are compared regarding CO_2 emissions, electricity production and component efficiencies. The first system that is studied is in operation today and uses biogas produced in the region as fuel in the ICE biogas buses. In parallel the combined heat and power (CHP) system delivers electricity and heat to households in the region. The second system that is studied is a system with electric buses and a CHP system that use biogas in the combined cycle turbine to deliver electricity and heat to the regional power grid and DHS. The use of this turbine will alter the fuel mixture for the DHS when heat from biogas combustion competes with heat produced by waste incineration.
Both systems represent smart energy systems in the sense that they are integrated technological systems providing a multitude of services. The basic condition for the case study is that the two municipal base services regional transport and district heating should be fulfilled. In addition, there will also be a production of electricity in the combined heat and power plant (CHP).

With the MODEST energy optimization software, the regional bus transport and DHS in the municipality of Linköping will be studied. System effects regarding CO_2 emissions and efficiencies will be analysed.

Nicolas Lamaison received his PhD from the Swiss Federal Institute of Technology in Lausanne (EPFL) in 2014. After 2 post-docs at the Bell Laboratories and at EPFL on the topic of two-phase cooling systems, he joined the National Institute of Solar Energy (INES-CEA) in France in 2016. His current research focuses on district heating networks and solar thermal modelling and optimization. He is the co-author of more than 20 papers in conferences and journals.

Storage Influence in a Combined Biomass/Power-to-Heat Production Plant

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Keywords: predictive control, power-to-heat, district heating, dynamic modelling, Modelica, MILP

The final energy consumption in France accounts for about 1900 TWh per year with a share of space heating and domestic hot water demands of about 35% [1]. The French energy planning of 2016 [2] has identified District Heating Networks (DHN) as a solution to reduce the use of fossil energy to supply this amount of heat. Indeed, due to their ability to massively distribute renewable and recuperation (R&R) energy, DHN are expected to deliver 5 times more R&R energy in 2030, to reach about 40TWh. In order to satisfy these objectives, biomass is expected to play a major role with 50% of the DHN mix in 2030 [3] with waste incineration, geothermal and solar thermal in a lesser extent to complete the renewable mix. However, biomass must be considered as a limited resource and other significant sources must be found for the future.
In parallel to that assessment, the concept of 4th Generation District Heating [4] emphasizes the need to interconnect thermal and electricity grids. The former would bring flexibility to the electricity network, notably regarding storage capabilities. Indeed, with the take-off of photovoltaic electricity, more and more intermittent energy must be integrated into energy grids, especially in summer. Power-to-Heat technology connected to a thermal inter-seasonal storage [5] is seen as a promising solution to store efficiently this amount of energy. The latter could then be added to the biomass to satisfy the renewable mix of DHN.
The present study addresses by simulation means the concept described above. The production plant considered is thus composed of a biomass boiler, a heat pump, a sensible storage and a back-up gas boiler (see Figure 1). A simulator of the system is built using Modelica programming language under the Dymola environment using the Modelica Standard library together with the 'DistrictHeating' library [6].
Considering predicted yearly variations of i) the demand for a given network and ii) electricity price together with specific investment costs, the production units and storage are firstly sized using a simplified MILP simulation over 1 year with the objective of reducing the total costs. Secondly, with the sized equipment, the simulated production unit is operated over 1 year on the one hand with usual expert laws and

with model based predictive control (MPC) on the second hand. The influence of the storage size on the cost and CO2 generation of the heat production is evaluated.

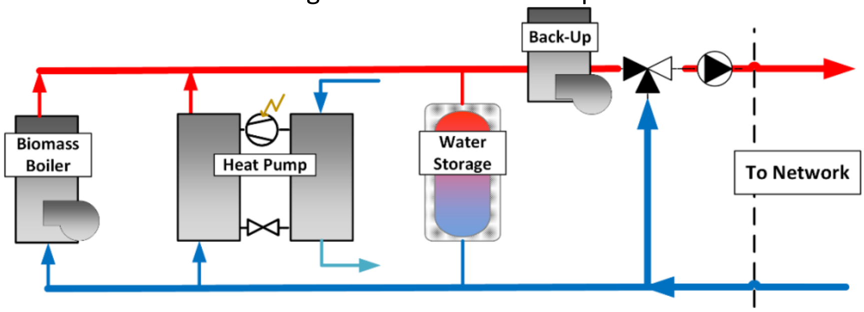

Figure 1: Simulated Multi-Energy Production Plant

[1] négaWatt, "Scénario négatWatt2011-2050: Hypothèses et Méthodes," 2014.

[2] République Francaise, *Programmation Pluriannuelle de l'Energie*. 2016.

[3] SNCU, "Enquête annuelle sur les réseaux de chaleur-restitution des statistiques 2014."

[4] H. Lund *et al.*, "4th Generation District Heating (4GDH)," *Energy*, vol. 68, pp. 1–11, Apr. 2014.

[5] H. Lund *et al.*, "Energy storage and smart energy systems," *Int. J. Sustain. Energy Plan. Manag.*, vol. 11, pp. 3–14, 2016.

[6] L. Giraud, R. Baviere, M. Vallée, and C. Paulus, "Presentation, Validation and Application of the DistrictHeating Modelica Library," presented at the Proceedings of the 11th International Modelica Conference,, September 21-23, 2015, Versailles, France, 2015, pp. 79–88.

Session 8: Future district heating production and systems

Luc Girardin holds a PhD in Engineering and is a scientist at the Swiss Institute of Technology in the field of territorial energy systems. **François Maréchal** holds a PhD in Engineering as a chemical process engineer. He is a researcher and lecturer in the field of computer aided process and energy systems engineering. He is also a lecturer in mechanical engineering, electrical engineering and environmental sciences engineering in EPFL.

Towards the 5th generation of district heating/cooling systems

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Keywords: future district heating and cooling systems, low-temperature district heating grids, smart energy systems, renewable district heating and cooling, CO_2 networks, energy autonomous cities

The increasing use of renewable energy is a deep going trend mainly supported by the sustained annual growth rate of solar photovoltaic (+45.5%), wind power (+24.0%) and Biogas (+12.8%). This evolution is going to increase the stress on the electricity and gas distribution networks. The development of advanced district heating and cooling (DHC) networks based on heat pumps that reach COP as high as 6 while providing up to 60% of the required electricity directly by the photovoltaic panels installed on the roofs of the district is providing a very good alternative.
The 5th Generation of district heating and cooling (5G-DHC) systems comes in the wake of the historical development of district heating systems with lower temperatures to harvest, distribute, recover and store heat from the environment using typically two distribution pipes for heating and cooling. Example of such 5G-DHC are tempered water DHC networks which recently evolved into "anergy loops" [ETH Zürich, 2017] which allow to recover and exchange wasted heat between buildings.
An alternative is to use CO2 as the heat transfer fluid. This new concept appears to be more compact, more economical and easier to operate than water-based systems [Henchoz et al., 2015]. Unlike the water network, the CO_2 network uses phase change to transfer heat between buildings, with 8/1.5 times higher volumetric heat capacity for heating/cooling and is controlled by pressure rather than by temperature difference. For each user, the heat is supplied or retrieved at the appropriate temperature by connecting decentralised heat pumps for heat/cold supply and environmental heat exchange. The electricity used in the heat pumps is produced by PV panels and cogeneration units. The annual energy balance is provided by power to gas (P2G) or power to liquid (P2L) systems that convert the electricity excess in the summer to supply electricity in the winter [Suciu et al., 2018].

In the paper, a comparative thermodynamic and techno-economic assessment of the 5th generation of district heating/cooling systems when compared with 4th Generation District Heating (4G-DH) and ultra-low district heating systems will be presented. In medium size EU-cities, our results show that with investment of 900-1300 €/cap are needed to convert cities into autonomous cities with PV area of 10-35 m^2/cap.

Henrik Pieper is a PhD fellow at the Department of Mechanical Engineering at the Technical University of Denmark. His current research is about the efficient use of heat sources and heat sinks for district heating and district cooling networks. Large-scale heat pumps are a major part of this research.

Large-scale heat pump integration model: A case study of Tallinn district heating

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Keywords: district heating, heat pumps, low temperature heat sources, optimization

Large-scale heat pumps (HPs) are proposed as a technology to efficiently utilize renewable low-temperature heat sources and to link the power and heating sector. Integrating energy systems may result in more cost-efficient and effective solutions than focusing on individual energy sectors for achieving a 100 % renewable energy system. Utility companies, like in Copenhagen, reported that 300 MW of installed HP capacity may be required by 2035 to supply sustainable and feasible cheap district heating (DH) without depending on biomass only. Such large capacities may not be achieved by the use of a single heat source. Instead, several heat sources may be required depending on available heat source capacity, accessibility, temperature level, investment costs and others.

In the present work, we present a model that may be used to plan the integration of large-scale HPs in existing or new DH areas. The model is able to identify both optimal HP capacities depending on the available heat sources and optimal choice of heat source used during the year by minimizing total investment costs and operational costs. Hourly calculations were performed over one year using linear programming. The HP model itself was based on two two-stage HPs connected in series.

The DH network of Tallinn, Estonia, was used as a case study. Six different locations were identified as potential locations for the integration of large-scale HPs. In addition, natural heat sources were included, which resulted in the following heat sources for the selection process: sewage water, seawater, groundwater, rainwater, ambient air, DH return water, district cooling as well as water from a lake and a river. Tallinn's DH network and its production units were analysed for one full year of operation on hourly basis to identify suitable HP capacities without compromising the operation of the combined heat and power (CHP) plants based on biomass and the waste incineration plant. The potential locations for HP integration as well as the considered heat sources are described and the seasonal variation and differences in heat source temperatures were analysed.

The results showed that the integration of large-scale HPs in the DH network of Tallinn is beneficial. Large-scale HPs could replace fossil-fuel fired boilers. It was found that 30 MW HP capacity could be operated on full capacity during 4500 h the year, 10 MW during 5300 full load hours or 1 MW during 7000 h a year. The model also identified the most suitable location and heat source for the implementation of large-scale HPs. Furthermore, the CO_2 emissions generated for the required electricity usage were calculated and compared to the operation without HPs. The case study of Tallinn DH showed how the developed model may be helpful for the integration of more large-scale HPs by identifying optimal HP capacities and the most suitable heat sources to use.

Gaétan Chardon is a PhD fellow at LOCIE laboratory in Chambéry, France. He is working on the European Interreg project ”PACs-CàD” with French-Swiss and academic-industrial partners. The subject of Gaétan Chardon’s PhD includes a model and experiments on heat pumps in district heating substations for 4 operating modes.

Absorption heat pumps in district heating networks: 4 operating modes

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Keywords: district heating, absorption heat pump, heat exchanger, cooling, upgrade, storage.

The aim of this article is to study the opportunity to integrate absorption heat pumps (AHP) in substations of district heating networks (DHN) by qualifying their performance. AHP can use heat from the DHN to match the building needs varying throughout the year, using different operating modes to either produce heat (at high or medium temperature) or cold and/or to store heat. The four operating modes considered are:

(i) The heating mode. The AHP is coupled to a heat exchanger, as explained in [1]. That allows to reduce the return temperature of the primary DHN to a temperature lower than the temperature of the secondary network. Therefore, the efficiency of this absorption heat exchanger can be higher than 1. This operating mode aims to reduce the overall heat losses in the DHN, to allow the recovery of medium temperature waste heat and to increase the share of renewable heat sources in the DHN.

(ii) The upgrade operating mode produces high temperature heat by using medium temperature heat from the DHN and rejecting low temperature heat to the ambient. The high temperature heat can be used for domestic hot water production or high temperature heating systems. This mode aims to reduce the temperature of the DHN, and thus to increase its efficiency.

(iii) In the cooling mode, the system works as a typical absorption chiller by using high temperature heat from the DHN and rejecting medium temperature heat to the ambient.

(iv) The storage mode is a special mode able to work with any other mode. Solution and refrigerant tanks are added to the AHP to store heat in a chemical form. This storage mode aims in a smoothing of the heat consumption peaks of the DHN.

A model was developed to simulate the AHP in DHN substations for each operating mode in typical operating conditions and for several absorbent/refrigerant couples. To compare the absorption couples, efficiency criteria were selected for each operating mode. The criteria used for the heating mode is the temperature efficiency as described in [2]. The chiller and upgrade modes use the COP (respectively cold and hot) as evaluation criteria. The energy density is considered for the storage mode.

The results of the simulations confirm the thermodynamic opportunity to use an AHP device in DHN substations to work under the different operating modes considered, but a deeper analysis should be performed to highlight the technical, economical and material constraints. Moreover, this study is a first tool to select the most appropriate absorbent/refrigerant couple regarding the operating modes and the operating conditions aimed at.

[1] C. Zhu, X. Xie, and Y. Jiang, ‘A multi-section vertical absorption heat exchanger for district heating systems’, *International Journal of Refrigeration*, vol. 71, pp. 69–84, 2016.
[2] X. XIE and Y. JIANG, ‘TEMPERATURE EFFICIENCY ANALYSIS OF ABSORPTION HEAT EXCHANGERS’, presented at the ICR2015 (International Congress of Refrigeration), Yokohama, Japan, 2015.

Matteo Caramaschi is R&D Engineer at METRO THERM A/S where he works with the development of novel heat pumps for residential applications and focuses on the modelling and optimization of their refrigerant circuits. Currently, Matteo Caramaschi is participating in the European H2020 project RELaTED which aims to demonstrate ultra-low temperature district heating technologies.

Novel Domestic Hot Water Microbooster Heat Pump in Ultra-Low Temperature District Heating

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Keywords: ultra-low temperature district heating, microbooster, heat pump, floor heating, substation, domestic hot water.

Ultra-low temperature district heating aims to improve overall networks efficiency and operational costs by reducing supply temperatures below 50 °C. Lower supply temperatures allow for: transmission and distribution heat losses minimization; performance improvement potential of heat generation plants; integration of low temperature heat sources with low marginal costs as solar, geothermal, excess heat from cooling processes, industrial waste heat, etc.
District heating supply temperatures of 35-45 °C can optimally fulfil requirements of new buildings with low temperature heating systems. However, these temperatures are not sufficient for domestic hot water preparation due to risk of Legionella growth and comfort requirements.
This study introduces a novel domestic hot water booster heat pump with built-in water storage tank located on the secondary side, connected in parallel to a floor heating system. The unit exploits district heating supply at 35-45 °C to directly pre-heat domestic water stored in a tank via a coil. Domestic hot water temperature is further lifted by the heat pump operation, which simultaneously cools the heat source to the desired return temperature.
Energy performance of the booster heat pump was measured on a working prototype and on field test units according to tapping profiles and methodologies of standard EN16147. Domestic hot water coefficients of performance of 4.8 and 8.0 were measured for heat source supply temperatures respectively of 25 and 40 °C and return temperatures of 22 and 30 °C.
Moreover, a system analysis of a building equipped with an ultra-low temperature district heating substation was carried out. Floor heating is supplied through direct heat exchange and domestic hot water through the micro booster solution. The overall primary energy consumption of the building, calculated with the Be18 software, resulted in 32.1 kWh/m^2, which fulfils the requirements of the Danish Building Regulation 2018. The proposed system was compared to a solution based on

conventional district heating supply temperatures. In the specific case, when the benefits of heat losses reduction in the transmission line are included in the overall analysis, the novel solution resulted to be a possible competitive alternative from a primary energy consumption perspective.
From an economic point of view, it was found that the most sensitive factor is the price of heat. If reducing the supply temperatures from 70-80 °C to 35-45 °C is not followed by a heat price reduction, for the final user, it is more convenient to have installed a district heating system with conventional temperatures of supply. The future trends of primary energy factors and energy prices may play an important role in the economic feasibility and the market development of this technology.
The study did not analyse the possibility to flexibly operate the booster heat pump only in periods of low electricity prices. An additional possibility to be investigated is to operate the heat pump booster to produce hot water and to simultaneously produce floor cooling during summer periods. In non-heating periods, using the building and the floor systems as free source of heat for the heat pump may allow for the reduction of yearly operational costs.

Diego Hangartner studied at ETH Zurich and finished with a Master's degree in Energy Science and Technology. He has worked as a project manager at Amstein + Walthert AG in the field of energy. Since 2013, he has worked as a research associate at the Institute for Building Technology and Energy at the Lucerne University of Applied Sciences.

Heat pumps in district heating and cooling systems – Case studies for Switzerland

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Keywords: heat pumps, low-temperature thermal networks, case studies, decentralized energy systems

Heat pumps play a key role in Switzerland's future heat supply. Up to now, they have mainly supplied single-family houses or apartment buildings. In the future, due to the increasing use of renewable energy and the potential of thermal networks, there will be a variety of possible areas of application for heat pumps, in different power ranges and for different temperature lifts. For example, heat pumps with a power range over 100 kW for high (> 60 K) or low (< 4 K) temperature lifts will be required (see figure below) as well as heat pumps that can deal with high source temperatures, requiring special designs from heat pump manufacturers.

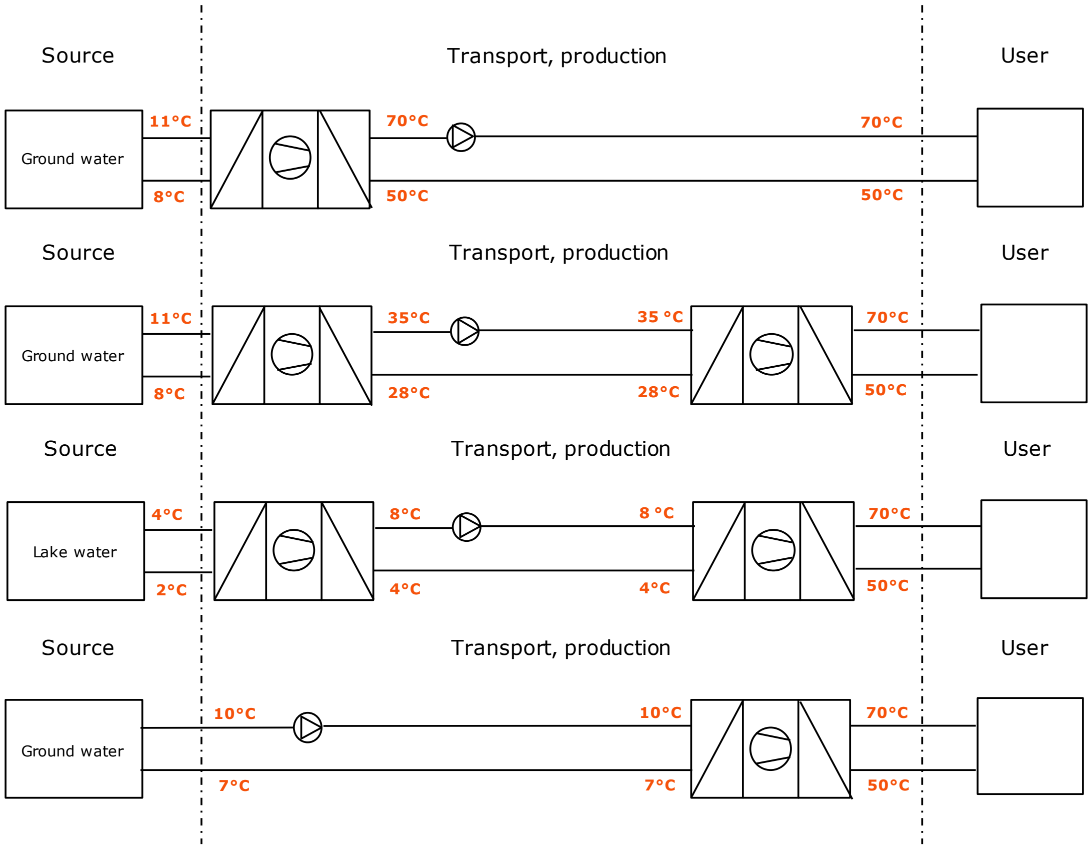

Figure 1: Different application possibilities for heat pumps in thermal networks when using low temperature sources.

Case studies from Switzerland and abroad will be shown and should serve as inspiration for further projects. Furthermore, application possibilities for heat pumps in thermal networks will be presented. The results are part of the research program «Thermal Networks» of the Swiss Federal Office of Energy [1] and the international project Annex 47 «Heat pumps in district heating & cooling systems» from IEA Heat Pumping Technologies Collaboration Programme [2].

[1] www.energieschweiz.ch/thermische-netze
[2] http://heatpumpingtechnologies.org/annex47/

Session 9: Energy planning and planning tools

Steen Schelle Jensen is Head of Product Management for Heat/Cooling Solutions at Kamstrup. His focus is on developing solutions that enable utilities to optimise their business and day-to-day operations by unfolding the full value of their meter data. Steen Schelle Jensen is inspired by helping customers on the journey towards a digital heat supply where decisions are based on facts rather than theory – because you cannot optimise what you do not measure!

Introducing SCADA for district heating distribution

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As the complexity of the utility industry increases on the way towards 4th generation district heating, so does the number of decisions utility professionals have to make every day. Theory, gut feelings and assumptions are not sufficient as the basis for managing an energy efficient production and running a distribution network closer to the limits – real-time decisions require real-time data. However, unlocking the full value of frequent smart meter data requires the right tools.

Kamstrup's new analytics platform, Heat Intelligence, is a direct result of our continuous investment in maximising the value our customers get from their data. At the International Conference on Smart Energy Systems and 4th Generation District Heating, we would like to elaborate on the thoughts behind this tool and the future opportunities we see it bringing. In addition, we will present concrete examples of the value it can create for utilities already today by providing them with the data-based decision support they need.

Analytics utilities can act on

Heat Intelligence enables utilities to go beyond observing meter data to refining and analysing them in order to uncover what caused them. Based on a model created by Kamstrup's own data scientists the tool combines meter data with facts about the network pipes to calculate and visualise how heat travels through the infrastructure. When utilities know what happens underground, they are able to better target their efforts and resources.

For example, if a building's forward temperature is lower than expected according to the Heat Intelligence model, the issue could be a defect service pipe or poor pipe insulation. If higher, it could be caused by a leakage or bypass. Whatever the reason, knowing the actual state of the network is the prerequisite for being able to act on it and reduce heat loss.

Heat Intelligence also gives utilities a precise picture of the load throughout their distribution network. This transparency shows how well their theoretic planning matches reality, so that they are able to validate their design rules. In this way, they can maximise utilisation of their capacity and target investments in network maintenance by e.g. estimating pipe lifetimes based on load and conditions rather than just their age. It also provides important knowledge for dimensioning new pipes and planning expansions of their supply area.

Data-driven disruption

Heat Intelligence is a unique and disruptive approach to smart data analytics first of all because it does not require utilities to invest in any additional field equipment – in or above the ground. Instead, the tool uses what is already out there: heat meters with temperature and flow sensors in all connected buildings.

Secondly, it provides a very high accuracy and statistical significance because the calculation model behind it is based on thousands upon thousands of measurements from smart meters – every single day. This adds the seasonal and historical perspective to reveal developments and trends over time, which is lacking with e.g. airborne thermography.

Finally, because the tool analyses measurements from all end points in the distribution network based on specific knowledge about its pipes, utilities can create virtual meters that can calculate temperature and flow anywhere in their network – even where there is no heat meter installed. This provides full transparency down to individual pipe sections. Ultimately, in the intelligent and integrated energy system of the future, smart meter data is the key not only to navigating effectively but also to unlocking the full potential of the opportunities it brings.

Matteo Giacomo Prina has worked at EURAC research, institute for renewable energy, since his graduation from Politecnico di Milano in sustainability and energy management. In November 2015, he started a PhD programme in Energy and Nuclear Science and Technology in collaboration between EURAC research and Politecnico di Milano. The title of his PhD project is renewable energy high penetration scenarios using bottom-up modelling.

Creating optimal transition pathways from 2015 to 2050 towards low carbon energy systems using the EnergyPLAN software: methodology and application to South Tyrol

Matteo Giacomo Prina[1,2] *(presenter), Marco Cozzini*[1]*, Federica Lombardi*[1,2]*, Henrik Lund*[3]*, Giampaolo Manzolini*[2]*, David Moser*[1]*, Ulrich Filippi Oberegger*[1]*, Poul Alberg Østergaard*[3]*, Roberto Vaccaro*[1]*, Wolfram Sparber*[1]
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Keywords: energy scenarios, photovoltaics, EnergyPLAN, multi-objective optimization, energy efficiency, transition pathways, emissions, cost-optimality

To face environmental and energy security issues, planning an energy system with high penetration of renewables is becoming increasingly important. Policy makers need tools capable of simulating energy systems over the years to identify relevant pathways and to develop effective supporting energy policies. Two main complementary approaches exist to bottom-up modelling of an energy system. The first approach optimizes the energy mix of a selected future year, while the second optimizes the transition pathway between the current baseline and a future year. Markal/TIMES and OSeMOSYS are examples of modelling tools for both approaches. However, due to computational issues, these tools usually adopt a time-slice approach characterized by 12 slices, which may be considered a low time resolution. This time-slice approximation is questionable given that renewables often are intermittent. To overcome the accuracy issue, in this paper we present a methodology for creating transition pathways based on our EPLANoptTP model. The model combines a multi-objective evolutionary algorithm with the EnergyPLAN tool, which allows for year-by-year simulations with an hourly time step. As opposed to the two complementary approaches detailed above, EnergyPLAN optimises the operation of exogenously defined energy systems; a feature that may can be exploited in this context.

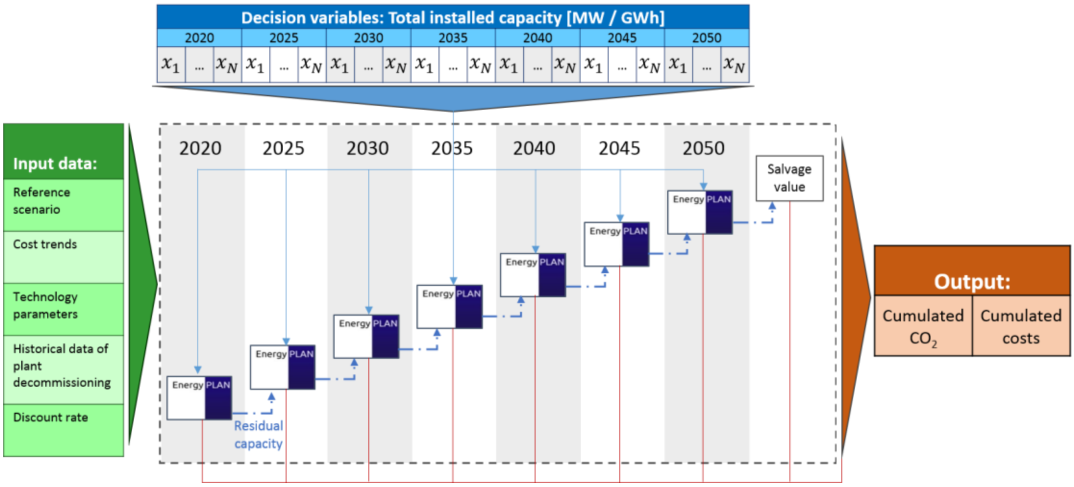

Figure EPLANoptTP model scheme. x_1, …, x_N are the decision variables of the optimization model.

We apply the methodology to the South Tyrolean energy system. The main inputs are the baseline created in EnergyPLAN, cost trends of the considered technologies, discount rate, technology parameters, e.g. efficiencies and capacities, historical data of plants and future decommissioning of all generation plants and technologies based on year of installation and lifetime. Each possible transition of the energy system found using evolutionary algorithms is evaluated by running sequential yearly EnergyPLAN simulations. For this case study, we have chosen to run EnergyPLAN in five-year steps from 2015 to 2050. After each EnergyPLAN simulation, the optimization algorithm determines the values of the decision variables producing the minimum cumulated costs and CO_2 emissions. The model includes a cost decrease of the technologies year by year and the need of power capacity due to the decommissioning of old plants. Decision variables chosen for South Tyrol are photovoltaics, photovoltaics plus batteries, hydrogen storage, energy efficiency in buildings plus heat pumps, and electric vehicles penetration for each five-year step.

The main conclusions are the following. This methodology enabled us to estimate cumulated CO_2 emissions in the period 2020-2050 and their reduction potential in relation to the cumulated costs. It considers the maximum potential of renewable energy and the age of the current power plants. The model provides a Pareto front of cost-optimal solutions for any target value of cumulative emissions reduction up to the maximum CO_2 abatement potential, and the total cumulated costs of each solution.

Mostafa Fallahnejad is a PhD candidate at the Energy Economics Group (EEG) in TU Wien. He is involved in the field of energy system modelling as well as heating and cooling planning. His research interest is mathematical modelling within the energy sector.

Impact of heating planning on the economic viability of District heating in Brasov-Romania

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Keywords: district heating potential, grid investments, policy assessment, Romania

The district heating (DH) system in the city of Brasov initially was designed to supply steam to the industry consumers and hot water to the residential consumers. By the shutdown of industrial consumers in 1990, the DH system got away from its primary purpose and became ineffective due to oversized pipelines and high heat losses in the grid. The lack of coherent policy in reviving the DH system as well as the loss of customers further deteriorated the situation for the DH system in Brasov.

In the recent years, the Local Counsel has established new actions toward increase of DH efficiency and consequently, increase of welfare in Brasov. These actions were coincided with supportive studies in the progRESsHEAT project – a H2020 project aimed to support the market uptake of existing and emerging renewable technologies. The outcomes of the project, among all, suggest an array of policy recommendations for Brasov's DH system. In this paper, we study the impact of those policy recommendations that aim at increasing the competitiveness of DH system. Those policies include the provision of long-term loans for investments into the network infrastructure and especially the implementation of heating and cooling planning to define zones that are preferable for DH.

In contrast to the methodology used in the progRESsHEAT project, where the DH areas were defined by areas around the existing distribution network, in this analysis, a GIS-based method and an optimization model are used for determining potential DH areas in Brasov. The GIS-based method uses the heat density map and the plot ratio map of Brasov for determining coherent areas in which DH distribution grid can be constructed economically. It also calculates the border-to-border distances of coherent areas. The optimization model has a revenue-oriented prize-collecting concept. On the one hand, it aims at maximizing the heat sales revenue in coherent areas and therefore, maximizing DH system coverage and on the other hand, it penalizes construction of transmission lines that connect coherent areas to the DH system. In this way, connection of remote coherent areas to the DH system will not be realized. The approach additionally allows for estimation of length and diameter of transmission lines, their associated costs and the economic corridor for laying the transmission pipelines. As the main constraint, the user-defined maximum allowed distribution and transmission grid costs should not be exceeded.

Finally, we will discuss if the outcomes of this approach correspond to the result of the progRESsHEAT project and if they substantiate the policy recommendations or if additional recommendations can be made.

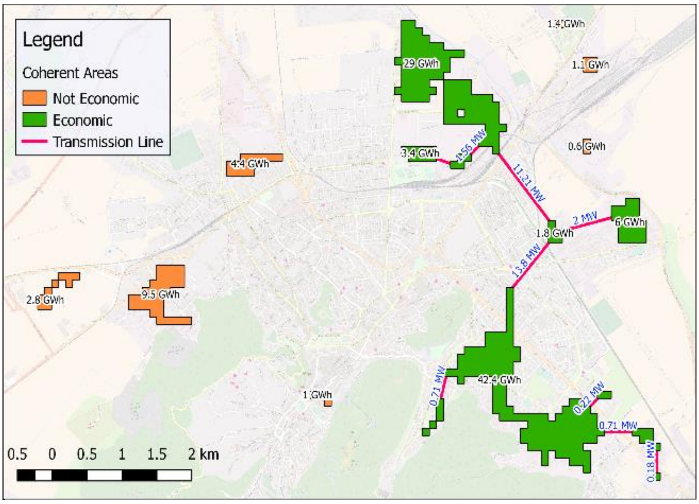

Fig. 1 model output for 12 years investment period (2018-2030) under the max grid cost of 20 €/MWh, 20% accumulated energy saving, 50% market share at the end of investment period, 4% interest rate, depreciation of 25y

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Integrated strategic heating and cooling planning on regional level for the case of Brasov

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Keywords: heating and cooling planning, district heating, renewable heating, heat savings

To reach the climate goals of the COP21 meeting in Paris it is essential to also decarbonise the heating sector. But because heating and cooling cannot be transported over too long distances its issues mainly appear on local and regional level and there is no system-wide solution. In former times there was no planning effort given to heating and cooling supply and the sector developed according to pure economics, availability and preference of technology without taking into account climate targets or long-term issues. To exploit the decarbonisation potential of the heating and cooling sector, integrated methods are needed on how to perform strategic heating and cooling planning on local and regional level. This planning process should include long term targets and the assessment of different heat saving and low carbon heat supply options accompanied by intensive and target-group oriented information campaigns and involvement of all stakeholders in order to ensure the achievement of the desired objectives. For example, district heating (DH) in general is seen as an important technology to decarbonise the heating sector mainly in urban areas. Especially DH needs an integrated planning approach including the development of heat demand into the assessment and to ensure a certain heat density by guaranteeing enough consumers making DH an economic effective solution. In this paper, the method and the results of an integrated strategic heating and cooling planning process performed for the case of Brasov is shown and certain parts of the process will be highlighted.

The method for the integrated strategic heating and cooling planning process presented in this paper is based on the case study of the municipality of Brasov, located in the centre of Romania, and was mainly developed within the Horizon 2020 project progRESsHEAT (Grant agreement no. 646573). The performed steps of the quantitative part within the planning process include: (1) Calculation of costs and potentials for heat savings for different building types. (2) Calculation of costs for heat supply with different individual heating technologies for the different building types. (3) Modelling of the existing district heating system and possible alternative supply portfolios for the future of the district heating system in energyPRO[1] to obtain the

district heating supply costs and the sensitivity of the costs to disconnection or to additional costumers. (4) GIS based analysis to divide the municipality into different types of areas according to the availability of a current district heating network or the feasibility and costs of expanding the network into adjacent areas. (5) For all building types and all areas within the municipality the most economic combination of heat saving level and the supply with district heating or individual technologies is calculated.
The results of the assessment show that at least a certain amount of heat savings, if performed when maintenance work is needed anyhow, is cheaper than all assessed heat supply options for all building categories. This applies especially for the old parts of the building stock but also for newer buildings. For the heat supply options chosen in combination with the most economic heat saving, the result is subject to the assumed framework conditions: Depending on energy prices, taxes, interest rates, depreciation times and the buildings characteristics, the cheapest combination with heat savings are natural gas boiler, heat pumps or biomass boiler. All assessed supply technologies have heat generation costs close to each other and their economic viability depends on the framework conditions. Especially the economic efficiency of district heating highly depends on the achieved share of connected customers within the network area. This shows the importance of integrated strategic heating and cooling planning to evaluate the needed framework conditions facilitating the implementation of cost optimal combination of heat savings with renewable and low carbon heating technologies.

[1] energyPRO is a modelling software developed by EMD International, http://www.emd.dk/energypro

Julian Wruk received his Bachelor's and Master's degrees in Engineering Management from TU Dortmund University, Germany. Before joining the Chair of Power System Engineering at the University of Wuppertal in 2016, he worked as a business consultant for the energy industry. His research interests are distribution systems, the integration of decentralised renewable energies and future network structures considering smart grid technologies.

An optimisation model for smart distribution network planning

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Keywords: distribution network planning, optimisation, evolutionary algorithm

A great share of Renewable Energy Sources (RES) has to be integrated into existing power distribution networks all over Europe to react to the climate and energy 20/20/20 objectives of the European Union. In contrast to the traditional central power supply by large conventional power plants, RES are mainly installed as Decentralised Energy Resources (DER) and are connected to the distribution networks. Hence, the medium and low voltage networks have to host increasing amounts of energy and even feed it back to overlaying networks. The sole amount of energy to be hosted as well as the fluctuating character of DER, in particular weather-dependent wind turbines and photovoltaic systems, lead to congestion and constraints (voltage rises, equipment overloads) in the distribution network. [1]
In order to supply the customers safely with electrical energy these constraints need to be tackled already when (re)planning the networks. In conventional power network planning the network is reinforced by installing costly new equipment, such as new lines, cables or more powerful transformers. Apart from that standard equipment, there are already innovative smart grid technologies and measures available, such as voltage regulators and re/active power management, which can technically effectively and cost-efficiently solve network constraints. [2] Given the described circumstances, the authors are now developing an optimisation tool to minimise the network reinforcement costs of given constrained distribution networks in order to derive guidelines on how to plan future smart distribution systems.
As the optimisation problem is particularly large and complex the authors have chosen a metaheuristical algorithm to solve it, which has already proven feasible in different approaches [3–5]. In contrast to the cited works, here, a genetic algorithm is used, in which additional smart grid technologies and measures are analysed. The objective is finding the optimal combination of technologies and measures in terms of costs, which solve occurring network constraints satisfactorily. As an input, model data of existing distribution networks is used. Based on scenarios of the forecasted feed-in (DER penetration) and load development (electric vehicles) generators and loads are distributed in the networks. Further parameters that are required are technical data,

such as the accepted deviation from the nominal voltage and maximal line loading, as well as economic data, such as the expenditures caused by the various technologies and measures used to solve the network constraints. The innovative technical measures regarded in the tool, apart from conventional measures, are on-load regulating transformers, line voltage regulators and active as well as reactive power management. For specific set points of feed-in and load level, the tool performs power flow calculations and determines the optimal solution. In the full paper, the algorithm as well as the concepts of the various network reinforcement measures will be described in detail.

The output of the optimisation tool is the specific technical measures to use at each analysed set point solving the network constraints. To relate to the European scope, network data from Germany, Norway and Portugal are used in certain use cases. Based on the output, the technical and economic feasibility of the network reinforcement measures are evaluated. In the full paper, preliminary results with selected reinforcement measures will be presented.

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Smart Grids Plus ERA-Net

This work was achieved in the scope of the transnational project *SmartGuide*.

Morten Hofmeister has 20 years of experience with district heating and project development, including EU projects facilitating knowledge sharing and capacity building. Now Morten Hofmeister is supplying solar thermal plants as Head of Projects in Savosolar, a Finnish producer of innovative large-scale solar collectors, turnkey projects in cooperation with local partners.

Solar Thermal – innovative technology and essential energy source in smart energy systems

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Keywords: solar thermal, innovative technology, low temperature district heating, renewable energy, energy system

Solar thermal has potential to be an essential and significant part of an energy system based on renewable energy sources, addressing mainly the heating part of the energy market. Large-scale applications include industrial as well as district heating applications.
Focus is on four levels; the collector itself, the solar field and the system in which the solar thermal plant is a part as well as the organization of the solar thermal project.
The solar thermal technology has been developed further by Savosolar, resulting in high efficiency and innovative design. Efficient heat transfer in the absorber profiles, coating technology as well as design of the collector minimizing heat losses are key features.
The solar field is designed according to key operation parameters, mainly the temperature levels, which define the flow rate, which is typically the limiting design parameter. Double stanchions facilitate an efficient solar field layout, minimizing the piping costs. Shared foundations enable better access to the collector rows.
Low temperatures in district heating systems facilitate higher efficiency from solar thermal plants. Hence, the advantage of an existing district heating system is a key point, and even more if considering the potential for increasing the efficiency of the district heating system by lowering the temperatures.
Industrial applications can have suitable consumption profiles as well as temperature levels. For both industrial and district heating applications, the long lifetime and low operation costs for solar thermal are key parameters.
On energy system level, solar thermal can be an essential part of the heat energy supply, supplemented by other energy sources and technologies. Combined with seasonal storages, increasing the solar fraction significantly, synergies with the electricity system can be obtained with application of heat pumps.
Local partners bringing knowledge on local energy systems is a key point in the approach of Savosolar. For dissemination of solar thermal, inclusion of local workforce

and competences is crucial to establish and obtain good solutions for solar thermal plants, which will be in operation for 20-25 years. Obstacles for solar thermal include relatively long planning horizon, with regard to land use and financing (relatively high investment costs compared to low operation costs).

In Denmark, the relatively widespread application of solar thermal in district heating systems was facilitated by the energy policy comprising subsidies and other regulation, and a district heating system with relatively low temperatures. Applicability and feasibility of solar thermal plants in other environments are being investigated and demonstrated in these years.

Roman Geyer is a research engineer in the competence unit Integrated Energy Systems at the Austrian Institute of Technology GmbH. His areas of responsibility include scientific collaboration, leading tasks and national and international projects with focus on district heating and cooling. He is experienced in the energy sector with focus on power plants and business models.

Barriers and Opportunities for Large-Scale Heat Pumps in Austrian District Heating and Cooling Networks

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Keywords: district heating and cooling, large-scale heat pumps, implementation challenges and solutions

Background and research focus: The integration of large-scale heat pumps (HP) into district heating and cooling (DHC) networks could be an increasingly attractive option for grid operators in times of increasing need for decarbonization, supply security and risk minimization in terms of investment costs. Additionally, they can provide flexibility to the power grid supporting and dealing with fluctuating renewables (e.g. wind, photovoltaic, etc.). While several plants are already in operation in the Scandinavian region, there are only a few case studies in Austria.

Methods: Relevant Austrian potentials and case studies for large-scale HPs in district heating networks were analysed and compared to other countries as part of the IEA HPT Annex 47[1]. The assessment was done based on literature research, interviews with plant operators and experts, inspections of demonstration plants and supported by static and dynamic calculations. Within stakeholder workshops different implementation barriers and possible solutions were identified. Using the canvas approach, the transferability of innovative business models to the current situation in Austria was identified.

Results: The main outcomes are:

i) A description of the market potential and economic opportunities of large-scale heat pumps in DHC networks in Austria,
ii) An assessment of existing case studies in Austria and international best practice examples and
iii) The identification of technological and non-technological enablers for increasing energy efficiency, the share of renewable energy or using excess heat in the different systems by using large-scale heat pumps.

Finally, recommendations for policy and decision makers as well as planners of energy systems in urban areas concerning the possibilities and barriers related to the implementation of heat pumps in DHC systems are derived.

[1] http://heatpumpingtechnologies.org/annex47/

Olatz Terreros holds a Master's degree in Industrial Engineering from the Technical University of Bilbao (Spain). She has been working for the Austrian Institute of Technology in the field of integrated energy systems since 2014. She is currently involved in national and international projects related to hybrid energy networks.

Investigating heat pump pooling concepts in rural district heating networks in Austria

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Keywords: district heating, heat pump pooling, business models, flexibility

Research focus: The development of renewable power generation and its volatile production characteristics are imposing challenges on the energy system in Austria. Therefore, suitable flexibility options for balancing are required (Esterl et al., 2016). Besides, the rural district heating sector is confronted with many biomass plants that are approaching the end of their technical lifetime and often operate unprofitably (Landwirtschaftskammer Niederösterreich, 2016). Heat pumps provide a link between the electricity and the heating sector and thus could provide flexibility for the electricity system and at the same time increase the profitability of the heat networks. The aim of the *fit4power2heat* project is to enable the economic integration of heat pumps in heating networks by creating synergies between heat and electricity markets.
Methods: Technical solutions and concepts of heat pumps in combination with thermal storage units are developed. For the techno-economic analysis, the investment and operating costs are compared and the respective heat production costs and revenues are determined. Based on the results of the evaluation, suitable business models are evaluated to support the integration of heat pumps in local district heating networks, the use of alternative heat sources and the coupling of the electricity and heating markets.
Results and conclusions: Four main results will be achieved: a) the development of technical solutions enabling a substantial reduction of the operational costs compared to a standard central heat pump integration; b) the economic evaluation of pooling of heat pumps in heating networks for several short-term electricity markets and analysis of the most interesting markets considering the possible revenues and its influence on the heat pump operation; c) the development of innovative business models considering the synergy effects between the electricity and heating domain and the different involved stakeholders; d) the transferability of the above-mentioned solutions to representative heating networks.

References:
Esterl et al. (2016) „iWPP-Flex Intelligentes Wärmepumpen-Pooling als Virtueller Baustein in Smart Grids zur Flexibilisierung des Energieeinsatzes“, Report, 2016

Landwirtschaftskammer Niederösterreich (2016) „Biomasse - Heizungserhebung 2015“, Report, 2016

Sylvain Quoilin is a professor at the University of Liège and an Energy Modeller focusing on smart energy systems. Sylvain Quoilin is a strong advocate of open science in the energy field.

Aggregation of flexible domestic heat pumps for the provision of reserve in power systems

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Keywords: flexibility, DSM, power dispatch, reserve

The fast spread of distributed power generation through the integration of renewable energy sources represents additional challenges for the management of the electricity grid. One main objective of this management is to ensure the balancing between electricity consumption and production. The intermittency of these renewable energies makes such balancing more difficult. Conventional power modulations on the supply-side are no longer enough to ensure security of supply, resulting in an increased need for flexibility of the demand-side. In this context, buildings can become key systems for demand-side management. Indeed, in the coming years, a substantial electrification of this sector is expected with increased use of electric/plug-in hybrid vehicles or high efficiency heat pumps. To manage all these flexible loads, a new entity, called aggregator, has emerged. Its role is to pool the flexibility of electricity consumers and either trade it on the electricity market or offer it as a service to electricity grid management entities.

This work assesses the amount of flexibility that could be reserved from a set of flexible residential heat pumps in a given geographical area. It addresses the problem of a load aggregator controlling a set of heat pumps used to provide both space-heating and domestic hot water. The flexibility of the heat pumps is unlocked in order to reduce electricity procurement costs in the day-ahead electricity market, while ensuring the provision of a predefined amount of reserve for real-time grid management.

The objective of the paper is two-fold. On the one hand, an aggregation method of large sets of heat pumps based on physics-based models and random sampling techniques is proposed. On the other hand, a combined optimization problem is formulated to determine both the optimal electricity demand profile to be bought on the day-ahead market and the cost associated to the reservation of a defined amount of power. The method is applied to a set of 40000 residential heat pumps in the Belgian context. Results show that these systems can provide up to 100MW of upward reserve for less than 50% of the current costs. The provision of downward reserve at competitive cost is hampered by significant overconsumption.

Wiebke Meesenburg is a PhD fellow at the Section of Thermal Energy, Department of Mechanical Engineering at the Technical University of Denmark. Her research focuses on the implementation of large-scale heat pumps into district heating systems and especially how to use them to supply regulation power in integrated energy systems. Her PhD is part of the EnergyLab Nordhavn project.

Dynamic behaviour of large-scale heat pumps and the implications for the potential to supply ancillary services – Experiences from EnergyLab Nordhavn

Wiebke Meesenburg[1] *(presenter), Tore Gad Kjeld*[2]*, Torben Ommen*[1]*, Wiebke Brix Markussen*[1]*, Jørgen Boldt*[2]*, Brian Elmegaard*[1]

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Keywords: large-scale heat pumps, dynamic behaviour, ancillary services, experimental data, dynamic model

Integrating the heating and the electricity sector has been identified as a promising approach to efficiently accommodate large shares of transient renewable energy like wind power. One approach to convert electric power into heat is to make use of large-scale heat pumps and electric boilers supplying the district heating grid. It is especially promising as district heating grids and thermal storages in the grid provide a large amount of heat storage capacity and thus flexibility as to when the necessary heat is produced. This enables the use of power-to-heat units to provide balancing services to the electricity grid. We propose to combine large heat pumps and electric boilers for this purpose.

It is known that electric boilers can react very quickly to signals from the electricity grid. However, most large heat pumps that have been installed to supply district heating, have been designed for base load operation, i.e. they have not been optimized to react quickly to signals from the electricity grid. Accordingly, there is a lack of knowledge about how fast large heat pumps can actually start-up and shut-down, how they perform during regulation and what the limiting factors are to be able to react faster.

In order to assess these questions, within this work the dynamic behaviour of a two-stage ammonia heat pump is assessed using the dynamic simulation environment Modelica. The model represents an actual heat pump that is installed in Copenhagen as part of the integrated energy system demonstration and research project “EnergyLab Nordhavn”. The data from the actually installed heat pump is used to parametrize and validate the model. The proposed regulation actions are tested on the real heat pump and thereby confirmed.

The results indicate that it is possible to supply tertiary reserves (15 min reaction time) from the heat pump and also supply secondary reserve services (5 min ramping time), when the heat pump is not switched off completely during regulation. The electric boiler can in these cases help to get smooth ramp characteristics. Further, it is indicated, how it could be possible to provide primary reserve (FCR-N 150 sec) using the electric boiler as down regulation capacity.

Session 11: Low-temperature DH and buildings

Leif Gustavsson has more than 30 years of research and work experience. His main field of research is systems analysis from a bottom-up perspective linked to sustainable development, especially building construction, energy efficiency, renewable energy, forestry and the interaction between these fields. The aim of his research is to increase the understanding of how resource- and cost-efficient systems with low environmental impact can be designed, analysed and implemented.

Primary energy and cost implications of supplying district heat of different temperature levels to new residential areas

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Keywords: low temperature, district heating, heat distribution losses, residential building areas, passive house

In the European building sector, major changes are essential to achieve the 2050 low-carbon and resource-efficient economy objectives. Building new energy-efficient building blocks using more resource-efficient renewable materials in combination with resource-efficient renewable energy supply systems can contribute to achieve national energy and climatic goals as well as the overall aim for a sustainable development. In this study, we analyse cost and energy efficiency of district heat distribution to a newly planned residential area in Växjö, Sweden. We consider four different land exploitations of the area, resulting in different heat demand density of the residential area. The buildings are either designed to meet the Swedish building code BBR 2015 or the Swedish passive house criteria. We design and evaluate the district heat distribution system for three different heat supply and return temperatures, 80/40^{o}C, 65/30^{o}C and 50/20^{o}C, respectively. We consider two different insulation standards for district heating pipes, Series 2 and 3. We consider conventional distribution technology and as well as plastic pipes for low temperature district heating. The energy performances of the buildings strongly influence the profile of heating demands. As a result, designs and performances of heat supply and delivery system are varied accordingly. Also, levels of district heat supply and return temperatures along with district heat pipe standards influence the design and distribution heat losses and therefore vary the costs and benefits of the district heat distribution network. However, cost- and primary energy effectiveness of each improved option depends also on the configurations and performances of energy supply systems. The results can be basis for planning and designing new building blocks and their energy supply systems to optimize investments, to reduce primary energy use and to increase the use of renewable energy in the built environment.

Dorte Skaarup Østergaard is a PhD fellow in the 4DH network. She performs dynamic simulation and evaluation of existing buildings analysing how to provide space heating for existing buildings with low-temperature district heating.

Heating of existing buildings by low-temperature district heating

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Keywords: space heating, radiator sizes, heating system control, fault detection

In this study, we present the results of four years of research on how to heat existing buildings with low-temperature district heating. The study consisted of three main parts. Firstly, we investigated the potential to use lower temperatures for space heating in existing buildings. This was investigated through analysis of the heating power of existing radiators in typical dwellings. Secondly, we investigated the barriers to realise this potential and lastly, we investigated how to overcome them. The results showed that there is a big potential to lower the space heating temperatures since as much as 80% of heating systems are currently over-dimensioned. Temperatures can often be lowered for much of the year even in under-dimensioned heating systems and replacing a few critical radiators could have a large impact on the overall space heating temperatures. The studies showed that poor control of the heating system is a main barrier for reduction of the temperatures. The results indicated that development of a new radiator thermostat with a return temperature sensor or the use of thermostatic radiator valves with pre-settings and proper pump control could provide robust solutions. It was found that extended service agreements with building technicians or district heating companies could be useful tools to identify and correct malfunctions in heating systems. In order to ensure robust results, continuous fault detection can be carried out based on data from energy meters or heat cost allocator devices. However, the customers must have an incentive to invest in a well-functioning heating system, and there is a need for personnel to offer the correct service-agreements and to drive the transition. The overall conclusion of the study is that there is a large potential to use low-temperature district heating for space heating in existing buildings. In order to realise this potential at the lowest possible cost, we need to identify the individual temperature levels that are suitable in the various district heating systems and make long-term plans for how to reach these temperatures.

Øystein Rønneseth is working with energy use in buildings at SINTEF Building and Infrastructure in Trondheim. He has a B.Sc. in Energy technology and M.Sc. within Energy use in buildings specializing on heating systems in energy efficient buildings. He is mainly working within FME ZEN, The Research Centre on Zero Emission Neighbourhoods in Smart Cities.

Is it possible to supply Norwegian apartment blocks with 4th generation district heating?

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Keywords: heating demand, apartment blocks, temperature requirement, existing building stock.

Direct electricity is widely used for heating purposes in Norway, leading to significant strain on the electricity grid during the heating season. Conversion to district heating (DH) is an effective method for reducing the need for large investments in the electricity grid.
Implementing 4th generation district heating (4GDH) will introduce some challenges. One of them is the ability to supply low temperature district heating to existing buildings, renovated existing buildings and new low-energy buildings. Other issues are related to risk of legionella in domestic hot water, increased return temperature due to limitations on mass flow, utilizing heat from low-temperature sources and integrating renewable heat sources. In this paper the minimum supply temperature in buildings has been evaluated based on effects of improving the thermal envelope and reducing the temperature levels for the heating system. The analysis focuses on whether the reduced supply temperature guarantees the comfort in the building, considering the coldest room with a heating setpoint of 22 °C. In turn, this will determine the minimum DH supply temperature.
The IEE project Tabula defines a building stock divided in 21 segments, consisting of:

- 3 types of buildings: single family house (SFH), terraced house (TH) and apartment blocks (AB)
- 7 age classes: Prior to 1956, from 1956-1970, 1971-1980 ,1981-1990, 1991-2000, 2001-2010, 2011-afterwards

A synthetic average building is defined for each segment, whose characteristics are representative of the most common features found in the segment based on best available knowledge. Each synthetic average building is described in three levels of energy performance (original, standard renovation and ambitious renovation) for a total of 63 archetypes. Based on these typologies, IDA ICE models representative for Norwegian apartment blocks have been developed. The ambitious renovation has not

been modelled, as the results are expected to be similar as for the newest age class. Instead, an intermediate level between the original building and standard renovation has been included, where only the windows are changed. Simulations are performed with two different dimensioning temperature levels for the radiators typical for Norwegian buildings; 80/60 and 60/40 °C.
The results include a comparison for the IDA ICE models to the heating needs found in Tabula. Hourly values for supply and return temperature, indoor air temperature in the coldest room and total mass flow rate in the heating system has been extracted and inserted in graphs relative to the outdoor temperature. Based on a minimum acceptable indoor temperature of 19 °C from the Norwegian building regulations (TEK), it should be possible to lower the radiator supply temperature from 80 to 60 °C for apartment blocks newer than 1971. For the older cohorts, the standard renovation is necessary in order to maintain comfortable indoor air temperatures. To conclude, it should be possible to introduce 4th generation district heating in most Norwegian apartment blocks.

Kerstin Sernhed has a broad research interest in district heating and the development of energy-efficient systems, demand side management, marketing strategies for district heating and electricity, development of energy services, as well as maintenance and status assessment of district heating networks.

Solutions and regulations to deal with legionella problems in district heating systems

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Keywords: legionella, low temperature DH, technical solutions, regulation for domestic hot water

District heating (DH) system efficiency can increase by lowering the system temperatures, which leads to lower energy losses and enhanced potential to include more waste heat with lower quality into the systems. To what extent DH temperature can be reduced is set by the ability to provide good indoor temperature and good comfort level on domestic hot water for the connected customers. Within new buildings with modern low temperature heating system such as under floor heating, the lower limit of supply temperature requirements from the DH supplier is not set by the demand for space heating but for the demand and regulation set in order to prevent Legionella growth in the domestic hot water systems. Legionellae are bacteria that naturally exist in freshwater environments but are also found in seawater and soils. Exposure to Legionella bacteria can cause two types of illnesses: Legionnaires' disease and Pontiac fever, where Legionnaires' disease being the more serious of the two.
This paper aims to give an overview over possible different solutions that inhibit legionella growth in domestic hot water systems attached to low temperature district heating systems. The paper also aims to summarise the prevalence of legionella cases in six countries (Sweden, Denmark, Norway, Finland, Germany and France) and compare it with the legislative framework within these countries regarding legionella prevention, in order to see if there are any correlation between low temperature requirements and high incidence of Legionnaires' disease.
Results show that the legislation in the six different countries varies with regard to temperature requirements to prevent legionella growth. It should be noted that today's legislation does not allow ultra-low supply temperatures in the DH system in most EU countries unless the regulated temperature levels in the customers tap water system can be achieved in some other way using local heating solutions, such as electric heat tracing, micro heat pumps or instantaneous water heaters. Of the countries included in this study, the ones with the lower levels of temperature requirements do have more incidences of Legionnaires' disease. Although causal relationship cannot be determined with certainty in this study, the results indicate that

there may be major risks of lowering the supply temperatures. Currently, ongoing research on legionella preventing solutions show some interesting results, but so far there seem to be no commercialized methods for killing legionella that are reliable, cost-efficient and long-acting, that do not require high temperature levels or short-term heating to higher temperatures.

Anna Kallert is a PhD fellow at the Fraunhofer Institute for Energy Economics and Energy System Technology in Kassel and the Technical University of Munich (Germany). Her research is dealing with low-temperature district heating supply, modelling and simulation of energy systems, exergy-based assessment and safe supply of domestic hot water.

Effects of decreasing domestic hot water supply temperatures for the efficient energy supply of buildings using low-temperature supply concepts – extrapolation to Germany

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Keywords: low temperature heating supply, domestic hot water supply, energy efficiency

With decreasing energy demand of buildings, the role of domestic hot water (DHW) preparation in the total building energy usage is becoming increasingly relevant. Hence, it is important to identify and quantify possible optimization measures and saving potentials in the supply of DHW. In this context low-temperature, supply systems provide new possibilities as they facilitate the efficient use of renewable energy sources (RES).
The work, presented as part of the abstract, is aimed at the investigation and the quantification of the effects of decreasing DHW supply temperatures in building energy supply. For that reason, the comparison of practically oriented scenarios of DHW supply is conducted as part of a simulation study. In particular, aspects of an energy efficient supply in new and existing residential buildings and the application of low-temperature supply concepts are examined. In addition, an estimation of the potential savings of energy and greenhouse gas (GHG) emissions for the heat supply in Germany was made.
The overall results demonstrate that lowering the DHW temperature supply promotes the increased use of RES (respectively low temperature sources) and thus increases the energy-saving potential of building energy supply. It is furthermore shown that the share of DHW preparation in the total energy demand of a building could be quantified with up to 50% in new buildings and with approximately 20% in existing buildings. The extrapolation to the overall heat supply in Germany illustrates that lowering the DHW temperature level enables a significant reduction in final energy demand and GHG emissions. The estimated savings are mainly caused by lower heat losses in the system as well as by the overall more efficient heat generation by RES. However, it has to be noted critically that aspects of drinking water hygiene (e.g. Legionella issues) have always to be taken into account. The results presented as part of this abstract show a partial aspect of the joint research project on "Energy efficiency and hygiene in drinking water installations (EE+Hyg@TWI)" funded by the Federal Ministry for Economic Affairs and Energy (FKZ: 03ET1234 A to D).

Anna Volkova is a senior researcher of the Department of Energy Technology of Tallinn University of Technology (Estonia). She defended her doctoral thesis in the field of district heating and CHP in Riga Technical University (Latvia) in 2008. Anna Volkova has worked as a posdoc researcher and later senior researcher since 2009 in the Department of Energy Technology, TTÜ. The main research topics are district heating, thermal energy storage, CHP and energy efficiency.

Development of a user-friendly mobile app for the 4th generation district heating promotion at the national level

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Keywords: smart thermal grids, mobile app, consumers, buildings, 4GDH

Sustainable development of district heating largely depends on the consumers. The consumers are considered to play one of the most significant roles in the district heating transition process towards the 4th generation: the consumers determine network growth and its parameters; they can influence heat loss through heat consumption density and return heating media temperature. Unfortunately, the lack of information and widespread consumer ignorance of interconnections and dependencies in the district heating system can lead to a situation where consumers are not interested in the development of the district heating system or might even choose other heat sources.

One of the possible solutions to provide information and educate consumers is a user-friendly, simplified mobile app that can show actual heat consumption structure, provide the possibility to compare the district heating supply with other heat supply solutions and provide information on how consumer behaviour affects the district heating system and how the district heating system transition towards the 4th generation will change the primary energy consumption and CO_2 emissions.

There are some mobile apps available to energy companies' customers, but, at the moment, there are no mobile apps aimed at promoting the introduction of sustainable district heating at the national level. This research will present mobile app that is aimed to promote district heating on national level in Estonia.

The importance of district heating in Estonia is very significant. The total annual heat consumption in Estonia is 6,700 GWh; in 2016, 69% of this amount (4,700 GWh) was supplied by district heating. In Estonia, there are 230 district heating regions. After the amendments to the Estonian District Heating Act in 2016, the connection to the district heating network is mandatory for all new or reconstructed buildings within the district heating region. Authorities and energy companies are interested in ensuring that consumers are informed about the advantages of district heating, as well as consumer behaviour impact on the district heating operation.

The authors will present the concept of the district heating promotion mobile app based on the three main input data groups. The first group includes heat production data for district heating regions of Estonia, with information about energy sources consumption structure, depending on the season, air temperature and heat load. The second group refers to consumers and various heat profiles. Typical heat load profiles for various building types and degrees of renovation, which can be visually determined by the user, will be based on the data collected. The third group is related to the actual case comparison with alternative solutions: local heating, average district heating parameters in Estonia, and development scenarios for district heating regions.

Nadine Aoun is a PhD fellow at CEA - France. Her research involves identifying semi-physical building models using only data accessible to a district heating system's operator, and implementation of model predictive control strategies to space-heating demand.

Load shifting of space-heating demand in district heating systems based on a reduced-order building model identifiable at substation level

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Keywords: grey-box building modelling, parameters identification, model predictive control

Buildings' space-heating demand is of fluctuating nature. It is fairly low during night-times or in absence of occupancy, while it reaches peak-values in the early-mornings or as the outdoor temperature drops. In a District Heating System (DHS), peak-loads are undesirable because they compel the operator to start-up expensive and polluting heat generation units. Meanwhile, buildings have an inherent thermal inertia, which offers flexibility in space-heating demand for a short-term heat storage and release without jeopardizing consumer's comfort. In our research, we propose a load shifting strategy of space-heating demand in DHSs using optimal predictive control based on a semi-physical building model, with a careful representation of building's thermal inertia. Two aspects of the work are presented; first, the building model identification and second, the model-predictive control strategy.

Building models for space-heating demand control at a DHS level shall fulfil particular specifications. Out of many modelling techniques, we narrowed-down the list to semi-physical reduced-order models. Such models have a reduced number of equations derived from physical phenomena under specific assumptions and feature a limited number of physically interpretable parameters. As they are dynamic ones, they are well representative of the transition state where the thermal inertia effect is mostly perceived. They are computationally fast and convenient for online optimization. Parameters identification is carried-out using historical data. Whereas in most previous works in this field historical data includes intrusive internal temperature measurements, we restrict our approach to a set of signals that are practically accessible to a DHS's operator. This novelty allows a widespread implementation of optimal control-related technologies in DHSs. We present the modelling approach and validation using a set of data generated by a realistic numerical simulator of a building with its radiators-heating system connected to a DH substation.

Model Predictive Control (MPC) is an optimal control method that aims at finding control variables' trajectories that minimize a cost function over a predicted future horizon, and that is based on a model of the controlled system. When implementing

MPC to control space-heating demand of a building served by a DHS, the control variable is the supply water temperature at the substation and the cost function to be minimized is a (possibly linear) combination of power price and comfort violation over a future horizon of 24-hours. The reduced-order building model is the mathematical link between the weather forecast (external temperature and solar irradiation), the comfort level (deviation of the mean set-point temperature from the standard comfort temperature) and the supply water temperature. The receding horizon principle implies applying the first output of the controller to the upcoming decision step, then repeating the optimization problem over the updated horizon. We describe the implementation of MPC for a building's space heating problem and compare its performance to a conventional control strategy.

Kaisa Kontu has both industrial and academic background. She is working in Fortum as a district heating production optimizer. She is also working with her PhD studies concentrating on business model development in district heating.

From partial optimization to overall system management – Analysis of district heating consumption data after consumers implementing demand response actions

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Keywords: demand response; district heating system; real-life consumption data

Intensified competition in energy markets and high targets for reduced emissions have prompted district heating (DH) companies to increase energy efficiency. Simultaneously consumers are increasingly interested in possibilities to decrease energy demand and costs through different actions. A general assumption is that demand response (DR) actions in heating stabilize consumption profiles, reducing peak demand and thus emissions of production. Several simulation studies have shown these assumptions to be true. However, much less is known about how real-life DR actions affect the heat consumption profiles of buildings, when building owners optimize their energy costs, and do changes in heat demand profiles affect the overall DH system. This study argues that DH companies should be involved in customers' DR actions as the best results are found when the DH system is jointly managed as a whole together with customers. This study analyzes real-life consumption data from 109 DH customers (hourly data from 2014–2017) in two different DH networks located in neighboring cities in southern Finland. All the 109 customers are residential block buildings, and 31 of them implemented DR solutions in their heating systems in 2016 with the aim to save energy and cut heating costs. The remaining 78 customers did not implement any DR solutions in their heating systems and are used in this study as a comparison group to DR customers. The study aim is to analyze changes in DR customers' heat consumption profiles after participating in DR actions and to compare the heating profiles of the two groups before and after the DR actions. For the analysis, the following parameters were calculated:

- Normative yearly and monthly heat consumption to describe energy saved through DR actions
- Annual relative seasonal variation
- Annual relative short-term variation (4 and 24 hours)

The preliminary results show that DR customers' energy consumption decreased after implementation of DR actions; customers' goals for DR, therefore, were realized. For some DR customers, the relative differences in the short term varied more after the DR actions. On a large scale, when heat consumption peaks temporarily coincided with a large number of customers, this might affect system-level consumption creating even more short-term consumption peaks and increasing the use of fossil fuel heat-only boilers. Figure 1 shows how the heat profile of one customer that had taken DR actions (black line) changed compared to other customers that had not taken any DR actions (green line, four comparison customers with the same location, purpose of use, construction decade, and supporting structure collectively).

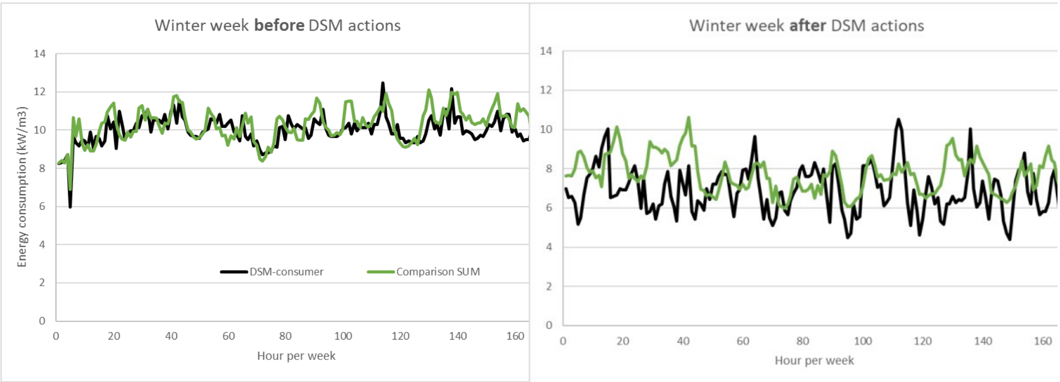

Figure 1. Heat profile of one customer (black line) for one winter week before and after DR actions

Sonja Salo is an Energy Systems Architect (MSc). In this study, a test bed in an office building was optimized with IoT radiator thermostats and intelligent demand management algorithms. The objective is to clarify how demand response on room-level accuracy affects the indoor environment of the building, indoor comfort and the heating load.

The Effect of Demand Response on Perceived Thermal Comfort in a District Heated Office Building

Sonja Salo[1,2] *(presenter), Energy Systems Architect; Juha Jokisalo*[2]*, Senior Researcher; Sanna Syri*[2]*, Professor; Risto Kosonen*[2]*, Professor*
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Keywords: heating demand response, district heating networks, comfort, perception, flexibility

Studies reveal that increasing flexibility in district heating (DH) networks can optimize CHP production and decrease the need for peak power production. As buildings consume about 40% of total global energy consumption, increasing flexibility with heating demand response can lead to significant economic and environmental improvements. With agreement, the buildings can consume energy when it is most suitable for the network. Therefore, the need for high-cost peak power plants decrease and CHP production can be optimized.
In this study, Internet of Things (IoT) and cloud computing is utilized to optimize buildings' energy usage, intelligent demand management algorithms are tested to optimize the whole energy system. The steering algorithms developed in this project are demonstrated in real buildings. This study is carried out in a district heated office building in Espoo, Finland. The steering algorithms allow temporary deterioration of the room space conditions, nevertheless causing as little dissatisfaction as possible. The user-centric approach aims to improve indoor temperature satisfaction in its entirety.
In the building, each room has been individually controlled by digital IoT water radiator thermostats. The thermostats are connected to a cloud server in which the target temperature is calculated. The cloud receives hourly price data for next 48 hours from the local district heating provider. Based on the price signal, the cloud changes the target room air temperature for the next hour, thereby increasing the thermal load flexibility in the building. The initial target temperature is determined by the user, and it can be changed throughout the study.
The study comprises one test period of two weeks. During the period, both demand response measures and placebo days were conducted. By controlling the set point of the radiator thermostat, the heating load could be changed according to the district heating operator's requirements. The amount of demand response was different room by room depending on the individual heat resistance of each room. Hence, demand response could be maximized without scarifying indoor comfort.
Thermal comfort is studied in the office rooms with a thermal dummy located at one workstation and with external sensors mounted to each room. Additionally, the users'

perception of thermal conditions is collected by using post-occupancy evaluation. Heating power at the radiator is estimated with temperature sensors and the radiator manufacturer's heating power equation.

Morten Karstoft Rasmussen works as a data scientist in the Analytics Team at Kamstrup. In close collaboration with utilities, academic institutions and other experts, the Team develops tools to extract information of great value from meter data. Morten Karstoft Rasmussen has a background in metrology and physics, and a long experience in analysing measurement data and systems.

Customer classification based on heat load pattern recognition

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Smart meter data can be used, together with pattern recognition algorithms, to identify certain types of consumption behaviour in an automated way. Such data-driven automated analytical tools play an important role, when moving towards 4th generation district heating, where utilities needs to highly optimize their production and distribution to stay competitive. Previously, utilities have mainly focused on using meter data to improve the energy performance of individual buildings, and, naturally, for billing purposes. However, as district heating becomes more complex and integrates many different heat sources, at also lower temperatures, its increasingly important to have an optimized infrastructure for transporting renewable and surplus energy to where it's needed.
By detailed analysis of the data from individual smart meters, profiles can be drawn for all consumers in the energy network and, depending on the focus areas of the utility, actions can be taken accordingly. The patterns detected can be related to faults in the customer's heat installation, or it may be related to certain unsuited behaviour, which is not beneficial for the energy network as a whole. As a proof of concept, Kamstrup have developed tools for costumer classification, focusing on identifying those who exhibits the so-called time clock operation. This kind of consumption, which is characteristic of schools, office buildings and other commercial premises with only daytime activities, contributes heavily to the morning peak load. By automated identification, a more focused effort can be undertaken, when consumers need encouragement to time shift their heat consumption. Some heat utilities are carrying out experiments where they are allowed to control a valve installed at the consumer, enabling the utility to cut off the space heating during the morning peak hours. In return, the consumer is financial compensated. This classification tool can then be used to identify those consumers where the supply needs to be temporary cut off. Numerous other load patterns may be relevant to identify. For instance, faulty heat installations, as illustrated in the figure below. In the future where the utilities have more control, also with the substations at the consumer side, such automated analysis tools are a necessity.

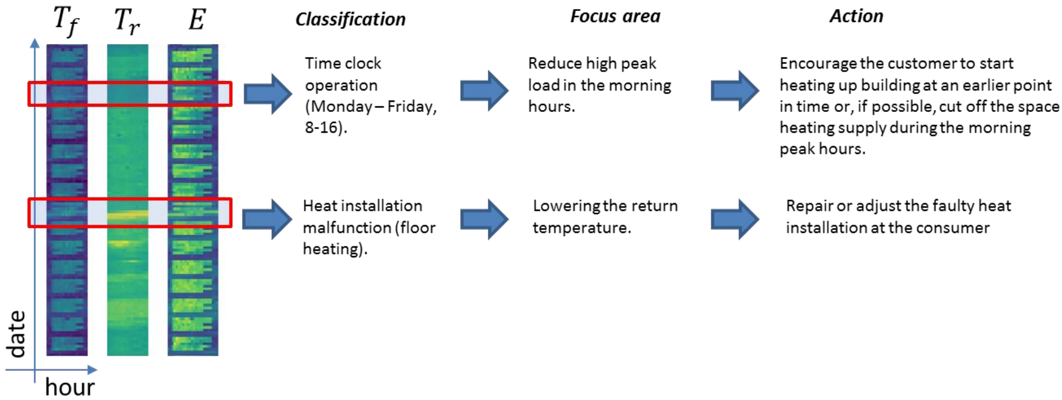

Figure 1: Illustrating meter data from a single consumer (far left), and how certain consumption patterns are recognized. By correlating all available data signals, a more detailed classification can be done. Here it is depicted how the algorithm identifies a consumer with time clock operation control, and a potential problem with the heating installation. T_f, T_r *and* E *denotes the forward and return temperature, and the consumed energy, respectively. The heat map colour indicate the numerical value of the concerned data signal. Also note that different colour scales are used for the 3 signals. Classification is automated, and appropriate actions can be taken by the utility based on these findings.*

Session 13: Smart Energy Systems

Ralf-Roman Schmidt is a senior research engineer at AIT and is responsible for the development of national and international projects. His research priorities are the optimized planning, design and operation of district heating systems in an integrated energy system context. He also holds key positions in international networks (IEA, DHC+TP).

District heating and cooling networks in an integrated energy system context – approaches within the IEA DHC Annex TS3

Ralf-Roman Schmidt[1] *(presenter), Andrej David*[2]*, Jay Hennessy*[7]*, Anton Inakiev*[6]*, Tanja Kneiske*[5]*, Ingo Leusbrock*[3]*, Daniel Muschick*[4]*, Dietrich Schmidt*[5]*, Olatz Terreros*[1]*, Edmund Widl*[1]

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Keywords: hybrid energy networks, sector coupling, integrated design and planning

Background: integrated energy systems[1] couples district heating and cooling (DHC), electricity and gas networks, enabling the storage and distribution of energy across them. Supply and demand follow different patterns in different domains, which leads to synergies in generation, storage and consumption. This results in an increased reliability, flexibility, supply safety and efficiency. Moreover, network coupling increases local utilization of renewables, avoiding problems in the distribution networks, as well as transmission losses. Also hybrid energy networks are a promising opportunity to manage and mitigate temporal imbalances of supply and demand in energy systems with a high share of volatile renewables, mainly PV and wind energy.

Aim and Methods: The IEA DHC Annex TS3 provides a holistic approach for designing and assessing hybridization schemes, focusing on the DHC networks and considering both technical (system configuration, operational strategy) and strategic aspects (business models, regulatory frame). These aspects will be discussed within the framework of the IEA DHC Annex TS3 in order to promote the benefits of DHC networks in an integrated energy system, as well as establish a common direction for the development and implementation of hybrid energy concepts. The IEA DHC Annex TS3 will connect existing national and international projects and thus benefit from interdisciplinary experience and exchange.

Expected results: The primary result of the IEA DHC Annex TS3 will be a guidebook including:

- Analyses of available technologies and synergies / application areas
- An overview of international case studies including simulation scenarios
- An assessment of the different methodological approaches and tools
- Recommendation on suitable business models, market design and regulations

Another results will be the development of an active community of academic and industry experts from different domains and fields. In this context, the cooperation with experts from ISGAN Annex 6 will facilitating the development of innovative solutions and scientific sound guidelines.

[1] Different alternative notations can be found in literature, e.g. hybrid energy networks, sector coupling, multi-domain networks, cross energy systems. However, since no standard definition is available, those notations are used synonymously.

Salem Al-Saleh is a PhD program student from Zagreb University. He has an EMBA Master degree from 2006 and a Mechanical Engineering Bachelor degree from 1999 from the USA. Salem Al-Saleh works for Nakheel in Dubai as a Managing Director of five departments. He is responsible for planning and directing all activities of 6 district-cooling plants that produce 40,000 tons of cooling capacity.

Comparative Analysis of District Cooling and Multiplicity Air-Conditioning Units – Case Study for Dubai

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Keywords: district cooling, chilled water network, Carbon emission, energy efficiency, water efficiency, conventional cooling system

As the United Arab Emirates (UAE) population increases, the energy demand is expected to grow to a nearly triple by 2030 and the Air-Conditioning represents the largest consumer of electrical power and it accounts for nearly 70 % of peak electricity consumption. The UAE government is exploring all possible new cooling technology to overcome this large power challenge and it seems that district cooling is an innovative way for lowering the energy consumption. Generating one ton of refrigeration using district cooling consumes about 0.92 kW of electrical power against around 1.75 kW per ton for conventional air conditioning. This paper will focus on the District cooling development in Dubai and the expected saving by transferring the cooling utilization from conventional cooling (Multiplicity of air conditioning units) to district cooling technology (Central chiller plant). This study presents both technical and commercial comparison between the conventional cooling and district cooling taking into consideration all possible parameters that can affect the cost and environment, such as the cooling equipment cost; life time of the plant, power and water cost, operation and maintenance, carbon emission etc.
The cost analysis has been conducted and revealed a cost saving with district cooling which can be attributed mainly to the operation efficiency operation of district cooling. The investigation on greenhouse gas emission shows that the cost savings are accompanying by a reduction in carbon emission. Furthermore, although the findings of this study are related to Dubai, the results are applicable to any district cooling operation in hot weather areas with dense population.

Gabriele Cassetti is an energy analyst at the Department of Energy at Politecnico di Milano. His field of work comprises, among others, renewable energy technologies, energy conversion, distributed generation and energy modelling.

A methodology for tertiary buildings cooling energy need estimation: a case study in Marrakech

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Keywords: cooling demand, district cooling, techno-economic analysis, GHG reduction, planning

The ever-increasing urban development together with the global warming trend over the past century inevitably demand sustainable and resilient solutions at urban scale. Smart district energy systems that can satisfy single or combination of energy needs such as the 4th generation of district heating are an example of promising solutions to tackle this issue. In the planning phase of these systems, several factors should be taken into account including energy sources, renewables, energy needs and storage.
However, in district energy systems planning the calculation of energy needs is a crucial step in making the investment profitable. Although several computational approaches and simulation software exist for estimating a single building heating and cooling energy needs, estimating the energy needs of building communities at district level is challenging due to a higher level of complexity. Existing engineering methods require a huge amount of inputs such as building geometry, envelope thermo-physical properties, HVAC systems, and schedules. Gathering and analysing these amounts of data is burdensome, costly and time-consuming, especially because of the diversity of existing buildings each with their own unique features.
The aim of this paper is to present a simple methodology for estimating the cooling energy needs of tertiary buildings that can be employed in sizing and design of a district cooling network. The methodology is based on building electricity bills to calculate yearly energy demand and on sol-air temperature to define the cooling load along the year. The developed method is then applied to a real case study: the feasibility analysis of a sustainable district cooling network for a hotel district in the city of Marrakech.
The designed system foresees a 23 MW_{cold} district cooling network, 4 km long, supplying 26 GWh of cooling to the touristic area. The reuse of grey water as heat sink for the chillers increase the sustainability of the system which leads to reductions in CO_2 emissions and refrigerant leakages by 46% and 34% per year respectively. The feasibility analysis includes techno-economic assessment and environmental evaluation of the district cooling system.

The results show the proposed methodology for cooling demand estimation is coherent with other existing methods in the literature. The bottom-up approach of this methodology relies on the seasonal variation of electricity bills and can be used at both individual and aggregate levels. The required measured electricity consumption input data usually have a good quality and can be gathered relatively easy.

This study is performed as a part of District Energy in Cities Initiative. Thus, all input data is gathered via surveys and questionnaires thanks to the partners involved in the project. Morocco being strongly dependent on fossil fuels importation, the purpose of this project is to assist the city of Marrakech in meeting the national energy strategy goals by accelerating its transition to a low-carbon and climate resilient society through a modern district energy system.

Hironao Matsubara is a Doctor of Engineering for Energy Conversion from Tokyo Institute of Technology (1990) and works as a chief researcher at the Institute for Sustainable Energy Policies. Research fields are statistics database, scenario studies, policy framework and business models of renewable energy in Japan. Hironao Matsubara has been the editor in chief of the Renewables Japan Status Report since 2010.

Comparative analysis of building and area heat demand and renewable energy supply in Japan

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Keywords: heat demand, renewable energy, Japan

In Japan, since the FIT system was launched in 2012, dissemination of renewable energy has been rapidly advanced mainly in solar power generation in the power sector. In 2017, the annual national average is 15.6%, hourly share has reached a maximum of 52%, and in Kyushu island, it reaches a maximum of 87%. More than 130 municipalities already have more than 100% renewable energy supplied annually over the region's electricity demand in the sector of residential, office, agriculture and forestry.
Comparing the heat sector with the power sector, the share of renewable energy to heat demand remains at a low level of a few percent, but some areas and buildings are using renewable energy such as heat of biomass, hot spring and solar thermal. However, compared with the power sector, statistical data of the heat sector is not well developed. Therefore, the heat demand by buildings and areas are analyzed comparing to the actual state of heat supply by renewable energy. By region, by using energy statistics by prefecture, allocate annual heat demand due to fossil fuels among municipalities, and estimate the supply of heat by renewable energy such as biomass, hot spring and solar thermal. For buildings, monthly estimates are made using hourly variation of heat demand of model facilities for hot spa, hotels, welfare facilities, etc., and the cost effectiveness of the possibility of biomass heat supply is analysed.

Session 14: Future district heating production and systems

Dagnija Blumberga leads the Institute of Environmental Protection and Energy Systems at Riga Technical University, Latvia. She has a Thermal Engineer Diploma and two steps doctoral degree diploma. Her main research area is renewable energy resources and energy efficiency, including 4th generation district heating systems. She has participated in different local and international projects related to energy and environment.

Solar DH system sustainability and flexibility increase forecast via power-to-heat technology integration. System dynamic approach

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Keywords: solar district heating, solar panels, power-to-heat, energy system flexibility, system dynamic

As the installed capacities of solar and wind energy production technologies grow, the flexibility of those intermittent energy sources becomes crucial. Alignment of energy production and consumption is one of the lately discussed topics. There are several solutions how to increase the ability of systems to adapt the energy consumption. Therefore, additional solution have been identified in order to utilize the excess power from the renewable energy sources when the power consumption is lower than the production rate. When such conditions occur, power can be transformed to heat (power-to-heat (PtH) concept) via electric boilers or heat pumps and used in the local or large-scale heating systems.
The system dynamic model has been developed by using hourly operation data from particular DH Company in order to evaluate economic aspects from PV technology integration. Development of renewable energy systems is complex problem with several variables therefore system dynamic modelling is suitable analysing tool. System dynamic modelling allows to evaluate the relationship between dynamic factors (dependency, energy demand, cost changes etc.) and the effect of different policies for renewable energy sources. The particular model evaluates the power-to-heat potential to forecast the solar power role in particular DH system and PtH concept for flexibility increase.
Results shows that integrating PV panels in DH Company is economically justified and that there are maximum levels of panels that can be integrated to maintain system profitable.

Jes Donneborg is responsible for driving Aalborg CSP's growth through the project development of Solar Thermal Plants across the globe. He has worked within the solar industry for 15 years developing various solar installations ranging from PV, air collector systems to domestic hot water installations.

Energy Hybrid Solution based on the Integration of Concentrated Solar Power

Peter Badstue Jensen, Executive Vice President Power Plants & Integrated Energy Systems, Jes Donneborg, Executive Vice Preseident Solar Thermal Plants (presenter), Hammam Soliman, Senior Sales and R&D Engineer
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Keywords: district heating, CSP, CHP, hybrid system, smart energy system, thermal energy, solar thermal power

System integrity and hybrid solutions are one type of reliability aspects in the field of energy production. In the recent two decades many efforts in the academic and industrial world of research, have been devoted to optimizing hybrid solutions that combines different type of energy sources. Integration of multiple energy sources have the advantage of increasing the system overall reliability through increasing its performance rate and efficiency. In addition, integrating of renewable energy sources (e.g. wind power, PV solar based) with the Concentrated Solar Power (*CSP*) provide the advantage of storing the energy at different thermal levels using different forms of Thermal Energy Storage(*TES*) systems. Such TES systems will allow the grid operators to overcome the absence of the renewable energy source due to weather fluctuations, and hence, increase the overall system availability, by producing Energy 'On Demand'.
As Aalborg CSP core competences is to bridge the academic research innovations with the industrial demands, it has developed an energy hybrid solution, based on the integration of CSP technology with other renewable and/or conventional resources. This concept has been the main motivation behind the establishment of the Combined Heat & Power (*CHP*) hybrid plants for District Heating (*DH*) purposes located in Brønderslev, Denmark. This abstract aims to present an even more innovative energy hybrid solution, that mostly consist of independently commercially well-proven technologies. The concept of integration is illustrated in Fig. 1.

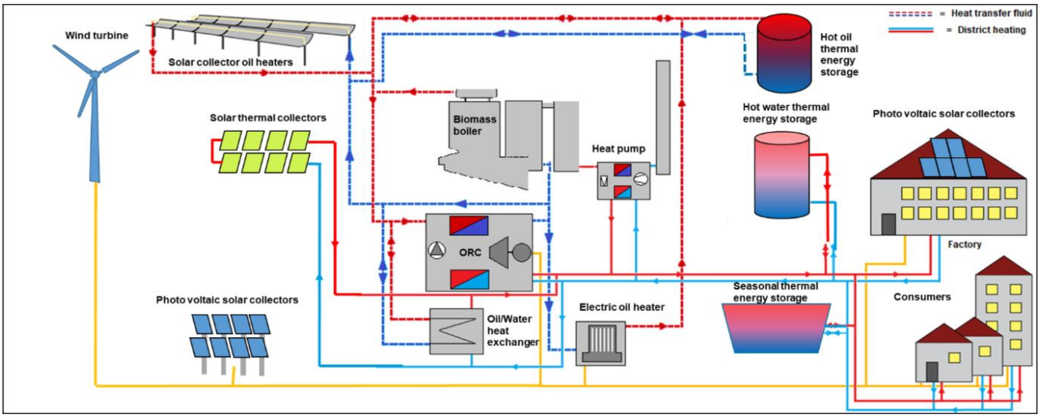

Fig. 1 Aalborg CSP Conceptual Hybrid Solution of Multiple Energy Resources for CHP Applications.

The main concept is to convert the electricity from grid, produced by either wind, or PV into storable high temperature thermal energy. And to create a common coupling point where the thermal energy directly produced from other renewable sources such as parabolic trough solar fields and biomass plants, are collected and stored. The thermal energy produced can, after storage, be used to supply electricity and/or heat 'On demand' via an ORC cycle, or to supply heat to consumption directly. Part of the energy can also, if required, be stored for seasonal consumption for DH purposes.
Different storage solutions, with regards to temperature and energy output demands, shall be presented in detail, in the final paper. Moreover, DH operating temperature levels required will be also investigated and discussed.

Borna Doračić graduated from University of Zagreb in 2016 and now he works as a research assistant. His work mostly focuses on energy planning of different systems, with a focus on excess heat utilization in district heating as a part of future smart energy systems.

Determining the feasibility of excess heat utilization in district heating system consisting of natural gas cogeneration and solar thermal

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Due to the high energy intensity of heating and cooling in the European Union, with around half of the overall final energy being used in this sector, it is necessary to reduce its primary energy consumption and the environmental impact. District heating systems are being increasingly recognized as a significant means for achieving these results. Different concepts can be used in order to increase the efficiency of these systems. Some of the examples are power-to-heat systems, use of renewable energy sources and excess heat utilization. The latter is especially interesting due to its high available amounts from different industries and services, which could cover the heat demand of the majority of European households and buildings in the service sector. Nevertheless, its potential is still highly underutilized and further research is needed to demonstrate the feasibility of its implementation in district heating systems consisting of different layouts. This is especially necessary if the concept of local deregulated heat market is implemented. The main goal of this work is to use the previously developed levelized cost of excess heat method to evaluate the feasibility of excess heat utilization in a district heating system which comprises of a natural gas cogeneration plant and solar thermal. The system was modelled on an hourly level to take into account the hourly excess heat availability, i.e. its distribution throughout the year. The supply cost curve was modelled to research the effect of the excess heat utilization on the heat price. For the supply cost curve modelling purpose, levelized cost of excess heat was used instead of the marginal cost in order to give a more accurate representation of the possible local heat market.

Marcin Bugaj specializes in hybrid energy systems of buildings and poligeneration from renewable energy. He is an assistant in the Department of Thermodynamics, MEiL PW Faculty; head of the Laboratory of Sustainable Energy Systems and employed at the Research Center of the Polish Academy of Sciences "Energy Conversion Renewable Sources".

Experimental study on the operating characteristics of a carbon dioxide transcritical heat pump combined with a single stage two-bed adsorption chiller and a PV installation in a low thermal district heating system: A case study

Marcin Bugaj[1,2], *A. MSc (presenter), Karol Sztekler*[2], *PhD, Krzywański Jarosław*[3], *Prof, Sebastian Bykuć*[4], *MSc, Patryk Chaja*[4], *PhD*

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Keywords: 4DH, renewable energy, heat pump, DHW, adsorption chiller, hybrid systems, solar energy

The Polish district heating systems are still based on the high temperature coal-fueled CHP. However, because of the declining operating temperature of user's installations, energy companies are willing to transform their systems in to the cascade district heating with the poligeneration sources. The high temperature transcritical carbon dioxide heat pump combined with the stratified heat storages could provide heat in wide range of temperature. That will allow to adjust the operating parameters into the older and the newer building heating installations. Moreover, combined with the adsorption chillers may allow to construct multivalent cold system. To ensure reduction of the primary energy usage photovoltaic installation should assure electric energy to drive all units.

The experimental stand constructed from the commercially available products has been set up. The high temperature heat pump could deliver the ice water and heat for the adsorption unit needs, ice water and heat for both DHW and adsorption process or it could operate only as a heat source working with higher temperature from the lower source. All electric energy was covered by local PV installation. Efficiency characteristics for a different operation scenario has been collected for the temperature range suitable for cascade district heating systems.

The main results show that application of the combination of the stratified heat storage with adsorption chiller presume for efficient use of heat pump as a cold source with waste heat development which causes those units more attractive in adaptation.

The obtained outcome allows to assess suitability of the proposed technical solution using it as a poligeneration sources in the cascade district heating system. They permit

to set the limits of application and to evaluate the energy efficiency of each working scenario. Moreover, the needed depth of renewable energy penetration could be evaluated what gives guidelines for the whole cascade system composition.

Peter Jorsal graduated as an engineer from Aalborg University in 1986. He has worked as a consulting engineer with district heating projects for 6 years. Since 1992, he has worked at LOGSTOR with sales management. Until 2015, he was at VP Sales for the Nordic Region and the service department. Since 2016, he has been the product manager for the LOGSTOR Group. Peter Jorsal is a member of the board at DBDH, a member of DHC+ and of 4DH.

Are Pre-insulated Pipe Systems according to the European Standards Over-engineered for Low Temperature Systems?

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A pre-insulated pipe system with steel service pipe or with a flexible pipe is used for distribution of hot water from the production plant to the end consumer in the following type of pipe systems:

- Transmission pipelines from the production plant to a city or between cities
- Distribution pipelines in the streets in a city
- Service pipelines as the connection between the distribution pipeline and the final consumer (apartments, institutions, one-family houses)

The minimum quality level of the pre-insulated pipe systems is defined in European standards for pre-insulated pipe systems for directly buried hot water networks with steel service pipe, polyurethane thermal insulation and outer casing of polyethylene or standards for pre-insulated flexible pipe systems, which are the following:

- EN253 – Pipes
- EN448 – Fittings
- EN488 – Steel valves
- EN489 – Joints
- EN15698 – Twin pipes
- EN13941 – Design and installation
- EN14419 – Surveillance system
- EN15632 – Flexible systems

The overall frame in the coming revisions of the standards for directly buried hot water networks with steel service pipe is a minimum service life of 30 years for systems, which are having a continuous operation with hot water at various temperatures up to 120 °C and at individual intervals with a peak temperature of 140 °C. The sum of these intervals must, in average, not exceed 300 hours a year.

Most projects at energy companies are required to comply with above European standards no matter the system temperature. Consequently, there is a risk that pre-insulated pipe systems according to the European standards are over-engineered for low temperature systems. In principle, the following will apply: The higher the

temperature demand, the higher the cost of specific pre-insulated components. The same goes for the static design of the district heating network.
Examples of this will be given in the presentation.
The question is, whether there is a need to extend the standards specifically to cover low temperature district heating pipe systems as well.

Luis Sánchez-Garcia is a Civil Engineer with a passion for District Heating and Cooling Technologies.

Reducing peak flow by use of plate heat exchangers for hot water preparation

Luis Sánchez-García[1] *(presenter), MSc Civil Engineering, Jens Møller Andersen*[2]*, MSc Energy Engineering*
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Keywords: district heating, DHW, plate heat exchangers, water tanks

Problem formulation

Many district heating networks are challenged in peak load situations. Often there have been expansions of the district heating grid that have led to the problem, that some central parts of the network have too small pipes. To compensate for that, it is common to increase the forward temperature and require consumers to use hot water tanks for hot water preparation instead of plate heat exchangers. However, conventional water tanks cause higher return temperatures and the district heating system becomes less efficient.

Scope

Domestic Hot Water (DHW) may be produced instantaneously by means of plate heat exchangers or hot water tanks. State-of-the-art plate heat exchangers are capable of operating at temperatures considerably lower than hot water tanks and therefore, its installation would enable a progressive reduction of district heating system temperatures. Nevertheless, district heating companies in Denmark are often reluctant to accept them and some still encourage their customers to install water tanks. The companies fear that their networks would not be able to manage the higher flows required by plate heat exchangers.

The aim of this paper is to investigate the use of both systems and asses their effects on district heating (DH) networks. The preliminary results show that plate heat exchangers are superior, district heating networks are perfectly capable of coping with them and the systems would benefit from a more widespread utilization.

Method

The DHW demand is estimated thanks to the patterns developed by (Jordan & Vajen, 2001). These demands are then introduced into a heat exchanger model that renders both the flows that need to be supplied by the DH network and the DH return temperature. Finally, a hydraulic algorithm by (Todini & Pilati, 1989) is coupled with a thermal model by (Benonysson, 1991) and applied into a small network of a typical Danish community.

Aleksandr Hlebnikov is the head of the research department in the Tallinn district heating operator company Utilitas. He defended his PhD at Tallinn University of Technology in 2010. The topic of the doctoral thesis was related to the optimisation of Estonian district heating networks. After working as an associated professor in Tallinn Technical University for more than 20 years, he continued his career in the district heating operator research department, investigating district heating improvement possibilities in Tallinn and other Estonian cities.

Lowering supply temperatures and its impact on the district heating system component parameters. Case study: town of Maardu, Estonia

Aleksandr Hlebnikov[1] (presenter), Anna Volkova[2], Vladislav Mašatin[1]
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Keywords: low-temperature district heating, pipes, supply temperatures, pumps, simulation, optimisation

One of the key conditions for the district heating system transition towards the 4th generation district heating is lowering supply and return temperatures. A reduction of temperatures in the DH system is required for both heat loss reduction and the ability to utilise renewable energy sources and waste heat. Despite the fact that the 4th generation District heating concept has already been implemented in some European DHSs, the district heating networks in Estonia can be described as 2nd or 3rd generation networks. Supply temperature range in Estonian DH systems varies from 75 to 120^{o}C, but due to the abovementioned advantages, DH companies are very interested in reducing temperatures. Lowering the temperature leads to changes to the district heating network operation and affects its components, such as pipes, pumps, heat exchangers, regulating valves, flow meters. The impact is particularly significant if the heat source is located rather far from the heat consumers.

Within this research project, the low-temperature district heating implementation potential for the town of Maardu (Estonia) was evaluated using NetSim simulation software. Maardu's heat supply comes from the waste incineration plant and the biomass-based CHP located 11 km from the town limits. Heat is distributed using DN500 and DN600 mm insulated pipes. According to previous evaluations, transmission pipes are oversized, and there is a potential to reduce the temperature and enlarge the heat flow.

As input data for the simulation, actual Maardu hourly heat demand data and outdoor temperatures were used. The district heating network operation parameters and operation boundaries for network components were investigated for three temperature regimes with maximum temperatures 110^{o}C, 90^{o}C and 70^{o}C.

The main parameters analysed are heat loss reduction, heat carrier flow and heat transfer coefficient, pump electricity use, primary energy savings and CO_2 emissions reductions.

Johannes Küchle received his Master's degree in renewable energy and energy efficiency in 2017. As a PhD candidate at the Department of Solar and System Engineering, he now focuses on dynamic thermo-hydraulic simulations of district heating networks.

Thermo-hydraulic implications of different design guidelines for 4th Generation District Heating Networks

Johannes Küchle[1] *(presenter), MSc, Isabelle Best*[1]*, MSc, Dr. Janybek Orozaliev*[1]*, Prof. Klaus Vajen*[1]
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Keywords: small district heating networks, thermo-hydraulic simulation, design guidelines

In the design process of new district heating networks, a common approach to determine the pipe diameters is to restrict their specific pressure drop at peak load conditions. In fact, many different design guidelines exist, ranging from less than 100 Pa/m to about 300 Pa/m (as shown in Figure 1), which leaves it open to planers which one to use. In a previous work [1] it was shown that allowing a higher specific pressure drop in the design process reduces the total distribution costs due to a reduction of investment and heat losses. This work analyses the impact of differing design guidelines on the thermo-hydraulic performance of the networks during the year and, in particular, in low-load periods using dynamic simulations.

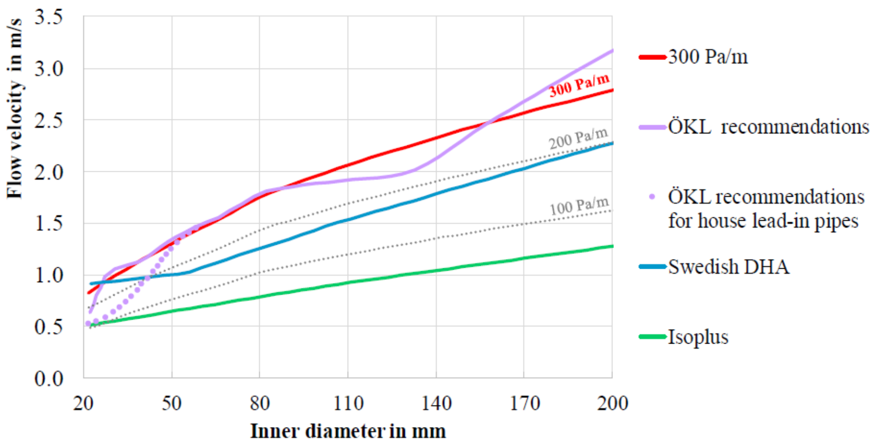

Figure 1: Design flow velocity curves as a function of inner diameter (reproduced from [1])

As a case study, a new housing development in Germany (total heat demand of about 1.8 GWh/a) with a 4th generation radial district heating network (total trench length of about 3 km, design temperature 70 °C supply / 40 °C return) is analysed. To this end, a computer model of the district heating network is built, and dynamic annual simulations are performed. The actual network states (pressures, flow velocities) during the year are analysed and compared with the design state.

Furthermore, several thermo-hydraulic effects of the different network designs are examined in detail. First, the network efficiency during low-load periods is examined by quantifying the excess flow due to bypass operation needed to maintain minimum supply temperatures and the consequential additional heat losses due to higher return temperatures. In this regard, systems designed for higher maximum specific pressure drops perform better, as they show less temperature degradation. Second, the pump energy demand throughout the year is analysed and compared for the different network designs as they influence both the pressure drops and volume flows to be supplied by the pumps. The presentation will show the results in more detail.

[1] Best I, et al.: Economic comparison of low-temperature and ultra-low-temperature district heating or new building developments with low heat demand densities in Germany. International Journal of Sustainable Energy Planning and Management 2018; Vol 16; 45-60. dx.doi.org/10.5278/ijsepm.2018.16.4

Session 16: Smart Energy Systems

Elisa Guelpa is an assistant professor at the Department of Energy Engineering of Politecnico di Torino. Dr Guelpa received her PhD in Energy Engineering at the Politecnico di Torino in 2016 with a thesis on the modelling of large energy systems. She is the author of more than 20 scientific papers concerning district heating networks, energy system optimization, thermodynamics, heat transfer and CFD.

Software for the optimal management of large district heating networks: a real application

Elisa Guelpa[1] *(presenter), Ludovica Marincioni*[1]*, Stefania Deputato*[1]*, Stefano Amelio*[2]*, Enrico Pochettino*[2]*,Vittorio Verda*[1]

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Keywords: network management, optimization, peak shaving, fouling, big data, forecast

Although district heating (DH) is a consolidate technology the research activity on this topic is more and more thriving. This is mainly due to its nature, which allows one integrating various energy sources and different types of plants. This offers a wide of range of possibilities for both design and management. In this framework, the chance of finding optimal solutions for maximizing performances and increasing flexibility is very appealing. Among the strategies for optimally manage DH networks, virtual storage obtained by rescheduling the operation of the heating systems in connected buildings, offers a variety of advantages. Rescheduling allows one flattening the thermal load to the plants, shaving peaks and filling valleys, bringing the following results: 1) the possibility of connecting additional buildings to the network without installing new pipelines; 2) a better exploitation of renewable energy sources; 3) a reduction in the heat produced by boilers, which are usually used to cover thermal peaks.

This work presents a software that optimally manages the buildings requests with the aim of thermal peak shaving. The software has been designed for large district heating networks (a few thousands of buildings). It has been tested on 10 distribution networks (more than 500 buildings) but it is tailored for being used to manage the whole network. The software includes various blocks:

1. The first for the data pre-processing; it allows extracting the required information from millions of files containing the historical data of the buildings.
2. The second for the forecast of the daily request evolution of each connected building (about 6000 in the entire network).
3. A block for the automatic evaluation of fouling in heat exchangers.
4. The optimizer, which provides the best schedule for all the buildings.

Results show that the software allows correctly predicting the building request evolution and to identify the fouled heat exchangers. The software guarantees a significant peak reduction that is shown to create benefits both in terms of primary energy reduction and of further possible connections.

Esmir Maslesa is a civil engineer with a Master's degree from the Technical University of Denmark. Currently, he is employed as an industrial PhD fellow. Esmir Maslesa's research field comprises facilities management, building performance, sustainability, IT systems and dynamic data.

The role of Energy Management System for heating consumption in office buildings – a case study of the Danish building and property agency

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Keywords: EMS, energy management, office buildings, building efficiency

The average energy consumption in non-residential building sector is at least 40% larger than in residential sector. Apart from energy intensive buildings like hospitals and restaurants, office buildings have also large electricity and heating demand during their operation.
The aim of this paper is to examine which role Energy Management System (EMS) plays for heating consumption in office buildings. The paper is based on a case study of the Danish building and property agency (Bygningsstyrelsen or BYGST) that manages around 800.000 m^2 office buildings and is currently in the process of implementing EMS. The study relies on field observations, document studies and interviews with energy specialists at BYGST.
The implementation of EMS is expected to enable energy managers at BYGST to collect reliable energy data and to bring deeper insight on energy performance in office buildings. The design solution for heating does not solely focus on heating consumption but provides also additional information on degree-day adjustments, consumption budgets, and cooling efficiency for each building.
The findings show that currently 65% of heating data is provided directly from the utility companies to EMS through remote readings. The heating data is collected every hour and used for analyzing heating consumption during working hours, outside of working hours, and in weekends. Furthermore, the EMS is used for benchmarking actual and expected energy consumption on hourly, daily, weekly and monthly level.
The paper contributes with new knowledge on how real estate organizations with large building portfolio can use EMS for energy management and reach better overview of actual energy performance in their buildings. Furthermore, the paper shows how hourly energy data can give more accurate calculations of climate impacts.

Jonas Hinker has been investigating the flexibility of multi-energy systems as a research associate at TU Dortmund, Germany, for three years. He has recently submitted his dissertation for examination and can thus be expected to receive his PhD in electrical engineering by the end of the year. He is currently looking for new challenges in strategical management and engineering.

A technology agnostic system platform for real options-based management of integrated energy systems: Long-term availability of new degrees of freedom for energy transition and optimal retrofits

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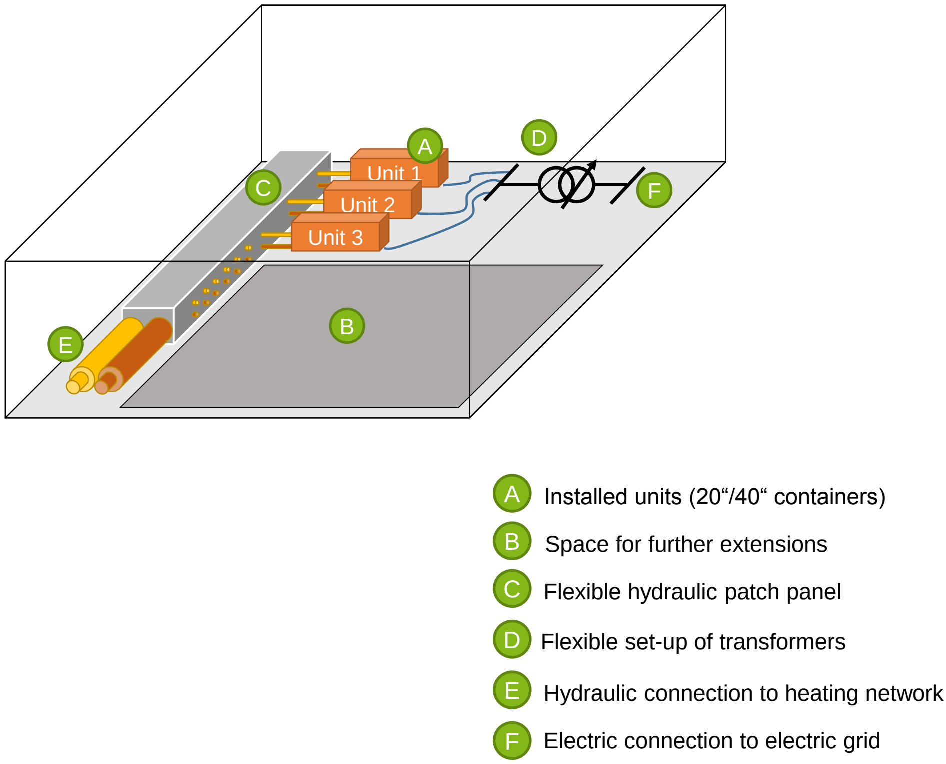
Keywords: optimal planning, multi-stage investments, real options-based management, multi-energy systems, energy infrastructure, district heating systems, combined heat and power, transition management

Due to uncertainties regarding prices, demand and regulation, the assuring optimality and cost-effectiveness of new combined heat and power plants can be challenging. Especially, long periods of amortization are a problem for innovative solutions. However, this problem clearly stems from the missing managerial options to retailor and retrofit a system easily after its implementation.

In this work, we therefore address heat suppliers of arbitrary size and propose a technical architecture that is tailored for two things: it allows for a successive implementation of efficient conversion and storage solutions and is able to accommodate arbitrary technologies due to the highly modular concept, i.e., all conversion and storage units are packaged in intermodal freight containers with standardized sockets and connectors for quick reconfiguration.

Consequently, an important degree-of-freedom is made available for the planning due to modularity. The real option to rescale the system is callable at any time: Whenever the market for relevant commodities like heat, electricity, natural gas, bio mass or other related (service) products like ancillary services changes, and operation is sub-optimal, the heat and power station can be easily retailored to the new necessities – a feature that is not given for conventional gas or steam turbines which would have to undergo capital intensive retrofits.

Making the system more modular also increases liquidity for the municipal utility or a GenCo: instead of an investment problem, there is an opportunity to optimize a portfolio. Naturally, a starting point for implementing such systems building on affordable technologies is easy to find, while migrating to more efficient generating units, and replacing boilers by power-to-heat units for integration of renewable energies is possible at any time. High transaction costs and planning overhead are simply avoided. For these reasons, such modular combined heat and power stations could in future be an elementary part of the energy infrastructure (like the electric grid is today). Economic and/or technical optimality is a lot easier to control, and with regard to the high pace of regulatory and market-based changes, it is an important solution for enabling the energy transition in future smart energy systems over years and decades.



Romain Lambert is a research fellow at Imperial College London and a data science and business development contractor, with an energy system modelling background and experience in the cleantech and proptech sector.

Scaling up digital technology for district heating – experience from large scale implementations of peak power optimisation

Dr. Romain Lambert[2] (presenter), Dr. Jaakko Luttinen[1], Dr. Edward J O'Dwyer[2], Mr. Jukka Aho[1], Mr. Lassi Viitala[1], Dr Christos Markides[2], Prof. Nilay Shah[2]
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Keywords: digitalization, demand response, load shifting, peak power optimization

Digitalisation is arguably the most important trend shaping the energy transition and district heating has undergone significant transformations in this area in recent years. A very important contribution of digitalisation to the district energy industry has been the implementation of intelligent 'Proptech' solutions for both consumer engagement and controls. Peak power optimisation using demand side management at the building level has been an important topic of research for a number of years in academic research community [1,2]. However, the rate of adoption of this type of technology by utility companies and real estate companies has been relatively slow, albeit with a notable increase in the last couple of years. The research focuses on the necessary conditions for a successful rolling-out of peak power optimisation, based on experience of implementing this technology on more than 10,000 apartments in the city of Espoo, Finland during the two previous heating seasons [3]. We discuss two of the most important factors of success which are scalability and the ability to integrate with a rich ecosystem of existing suppliers. Based on analysis of the data from the two preceding heating seasons, peak power reduction averaged 17% with a three to four-year payback. During the previous two heating seasons, both local peak shaving and global demand response were implemented using a production price signal from the local utility and the technical and organisational challenges of integrating with the existing systems are presented. It is shown that a local peak power optimisation scheme is efficient in optimising building level power peaks (17% reduction on average) while maintaining regulatory indoor conditions without affecting the number of resident complaints. However, fluctuating supply water temperature and thus radiator surface temperature might lead into a feeling of draft if not correctly compensated. Furthermore, the findings reveal that a precondition for non-contradictory targets for building owner and a utility company requires alignment of the district heating pricing models used in billing compared to actual power requirements of individual buildings and price signals used. Implementing a demand response control with a global price signal will in many cases result in an increase of building level power peak and thus increases the total cost of district heat for building owner if the pricing model used in billing is not updated accordingly. Also, practical issues such as closedness of traditional automation systems and organisational resistance from building maintenance are presented in relation to the implementation of large scale peak power optimization. Despite all the challenges it is shown that cost effective methods to overcome all presented issues can be implemented with relative ease and no concrete obstacles are in the way of city-wide roll-out of such systems.

References:

[1] Johansson C, Wernstedt F, and Davidsson P. Deployment of Agent Based Load Control in District. Heating Systems. First International Workshop on Agent Technologies for Energy Systems, Canada, 2010.

[2] Esko K. Juuso, Smart Integration of Energy Production. In: Proceedings of the 58th Conference on Simulation and Modelling (SIMS 58) Reykjavik, Iceland, September 25th – 27th, 2017.

[3] Leanheat Oy, Case Espoon Asunnot, 2018 https://leanheat.com/2018/02/05/case-espoon-asunnot

Session 17: Low-temperature district heating grids

David Forbes Pearson is Director of Star Renewable Energy, Board Member of Scottish Renewables and Vice Chair of the Heat Pump Panel in RHC Platform in Brussels. In 2009, he proposed to Drammen Fjernvarme to utilise ammonia for their proposed 900C heat pump rather than a Freon solution.

Network Characteristics to Optimise the Efficient Application of Ammonia in District Heating systems

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Keywords: ammonia, heat, pump, HFC, district, heating, Drammen

As the Paris agreement seeks a near total phase down of Carbon emissions, the method of district heating has become a topic of intense discussion around the World.
Technologies such as Biomass and Energy from Waste, although prevalent are strictly not sustainable or scalable so attention has shifted to large Heatpumps.
Simultaneously the Kigali Amendment to the Montreal Protocol leads us to low GWP solutions. Whilst newer synthetic working fluids would appear useful this paper will identify ammonia as more suitable for future deployment and will present an economic assessment of two options (HFC and Ammonia) showing the advantages of Ammonia.
Drawing on 7 years of operational data from Drammen, deployed 2011, this is still the world's largest 90C ammonia heatpump and consistently delivers neatly 70GWh per annum of heat boosted from the salt water fjord.
In a simple market where one purchases electricity and sells heat the efficiency is paramount and Drammen enjoy a 20% higher efficiency than similar HFC systems.

Dietrich Schmidt is Head of department at Heat and Power Systems of the Fraunhofer Institute for Energy Economics and Energy System Technology in Kassel Germany. He works with energy supply and the use of infrastructures with a key interest in low-temperature district heating. He coordinated the recently completed IEA DHC Annex TS1 activity.

District Lab – Experimental facility for innovative district heating systems on a community level

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Keywords: low temperature district heating; research facility; decentralized feed-in; grid operation

Especially low temperature district heating is recognized as a key technology for the (cost-) efficient integration of renewable energy and waste heat sources in our energy systems. Energy system studies indicate that a further development of low temperature district heating systems is needed for a decarbonisation of the heating sector. A deployment of local district heating schemes is mandatory to reach the set climate goals. On the other hand, we see that district heating is also put into question. To face these challenges research on innovative district heating concepts integrating decentral feed-in of renewable energy is needed.
The Fraunhofer IEE has started to set up a new research and experimental facility as a test and development platform for innovative district heating systems in close cooperation with industry partners. This facility consists of a real district heating grid in a lab-scale and expands the possibilities of the already existing facilities. This experimental environment is more flexible than experiments compared to tests in real operating district heating grid (demonstration) since no public utility mandate is connected to the District-LAB facility. Tests with variating temperatures and pressures can be conducted; new components and operating mode can be tested. On the other hand, the real behaviour of components and systems can be tested in a real life environment, simulation models can be validated in this facility.
First project ideas are with three different fields as the tests of new operational strategies (e.g. dynamic and changing boundaries for feed-in and utilization, grid operation with new temperature regimes, dynamic pressure and temperature changes) or tests of components (as piping systems, heat exchanger / sub-stations, pumps, control elements) or within the field of the development of simulation tools and validation (e.g. static hydraulic simulations incl. heat losses, dynamic simulations of control strategies and pressure changes).

The paper presents a more detailed description of the facility and the planned research activities to foster the discussion about needed research and to invite possible partners from academia and industry for future cooperation.

Federico Bava is a project manager at PlanEnergi, a Danish consultancy working in the field of renewable energy. He is currently working on international research projects for innovative energy solutions, such as neutral temperature district heating (FLEXYNETS) and power-to-heat-to-power system (CHESTER). He holds a PhD degree from the Technical University of Denmark on the topic of modelling solar collector fields for district heating applications.

Recommendations for Combined District Heating and Cooling Networks

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Keywords: ultra-low temperature district heating, district heating and cooling, excess heat, networks, heat pumps

Ultra-low district heating (DH) includes both benefits and drawbacks compared to conventional DH and individual supply. Using such networks also for district cooling can create a synergy between heating and cooling demands, increase the potential for utilising low-temperature excess heat and reduce CO_2 emissions. FLEXYNETS (www.flexynets.eu) is a Horizon 2020 project under grant agreement no. 649820 ending in 2018 with an aim to identify the circumstances where such a concept is most feasible including a comparison with alternative supply options. Various parameters affecting cost and performance have been analysed which leads to general recommendations for combined district heating and cooling (DHC) networks.
The FLEXYNETS concept includes a two-pipe DHC network operating at low temperatures (e.g. 20-30 °C). Reversible heat pumps (HP) at the consumers draw/reject heat from/into the network depending whether they operate in heating/cooling mode, bringing the heat to the temperature level required by the consumer. The two types of thermal load balance each other (at least partially), thus saving primary energy in a central DHC supply point. Lower operating costs on one side are counteracted by the higher investment costs of a FLEXYNETS system, mainly for the installation of a large number of heat pumps. Besides this, a FLEXYNETS network operates with a lower temperature difference (e.g. approx. 10 K) than conventional DH (approx. 30-40 K) and hence requires higher flow rates, provided the same thermal power. In turn, the lower delivered thermal power (because the HP will contribute with electricity to the heat supply) and lower pipe insulation requirements, contribute to keep the network cost at the level of conventional DH. The feasibility of the FLEXYNETS concept is improved by:

- Contemporary presence of heating and cooling demand.
- Availability of relatively large amounts of cheap excess heat at low temperature, possibly in phase with the heat demand.
- Economy of scale benefits for the purchase and installation cost of the heat pump substations given the number of installations per network.

From the environmental point of view, the FLEXYNETS concept can reduce CO_2 emissions, because of the balancing out of heating and cooling loads, the possibility of using various excess heat sources and the possible integration of solar thermal collectors, whose efficiency is enhanced at low temperatures. Because the FLEXYNETS concept entails a higher electricity consumption compared to conventional DH, it is most suitable in connection with (present/future) electricity networks mainly based on renewable energy sources in order for the overall system to be environmentally friendly.

Gašper Stegnar is results-driven and determined with a passion for energy modelling. His field of work is R&D in the areas of building energy retrofitting, energy systems, national regulations, EPBD transposition, environmental impact of buildings and building thermal simulations. Gašper Stegnar enjoys converting research into action, so he is constantly involved in promoting his work to policymakers, industry, and academics across a range of formats.

Pathway for shallow geothermal energy potential in district heating systems development in Slovenia

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Keywords: district heating, heat pump, geothermal energy, spatial constraints, GIS

Slovenia is setting energy and climate policy paving the way to low carbon society based on renewable energy by 2050. That transition should include, beside extensive heat savings and traditional use of biomass for heating, the large-scale implementation of district heating in urban areas and electrification of the heating sector, primarily using heat pumps in rural areas and introducing the smart energy systems approach based on a cross-sectoral use of all grids. In this analysis, the potential for district heating and use of geothermal energy for heating in Slovenia is identified, based on geographical information system (GIS) mapping of the heat demand and shallow geothermal energy potential.
Highly efficient district heating systems have a significant potential for primary energy savings and reduction of greenhouse gas emissions through the utilization of waste heat and renewable energy sources, including intermittent ones. These potentials are still highly underutilized in Slovenia. In order to ensure the optimal level of district heating penetration in the heating sector, a comprehensive analysis was performed to determine the actual and future heat demand, considering implemented and foreseen energy savings measures. Based on heat demand, the technical and economically feasible district heating potential was determined using the GIS heat map. A geothermal energy potential assessment methodology was developed and results incorporated in the heat map, providing necessary data for future analysis and planning, either centralised or decentralised smart heating systems.
Head demand mapping is based on a bottom-up model of the building stock in order to ensure sufficiently accurate and comprehensive analysis of energy balance of the residential and non-residential building stock. Since the heat demand models are physics-based, the number of inputs required to estimate the energy consumption of each building is large. The model integrates four publicly available databases, by which it is possible to determine the current state of the thermal envelope and technical

systems. The approach used builds on the GIS-based data of energy demand for heating and domestic hot water.
Large scale assessment of shallow geothermal economic potential (SGP) for heating in Slovenia was performed. It takes into account water-water systems in alluvial aquifers and borehole heat exchangers (BHE) in other geological layers. The main criteria for BHE potential analysis were ground temperature, thermal conductivity, heat flux and heat capacity. The criteria of one-half of the BHE depth as a minimum distance between different neighbouring BHE installations was introduced in order to eliminate thermal influence on each other. Furthermore, depending on the presence of special geological conditions or protected areas, areas of narrowest and narrower water protection areas and protected artesian aquifer were excluded from the analysis. Spatial distribution of SGP along with economic viability for six different building types and usage profiles was identified for Slovenia on 100x100 m grid using GIS.

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Bente Johnsen Rygg is working as an associate professor at Western Norway University of Applied Sciences, Campus Sogndal. Her research is concerning local development of renewable energy, community energy projects, the role of municipalities in renewable energy projects and the social acceptance of renewable energy. She currently teaches at the bachelor's programme in Renewable Energy and master's programme in Climate Change Management.

The role of 4th generation district heating in a future energy system based on hydropower

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Keywords: 4th generation district heating, hydropower, smart energy systems, EnergyPLAN, renewable energy systems

District heating has been used for many years in many European countries, and from the perspective of the EU, district heating is considered to become an important component of the future European energy system. At the same time, the status of the diffusion of district heating can differ greatly even between neighbouring countries – not least in the Nordic region. In Denmark, Sweden and Finland, for example, district heating has a long history and is a major contributor in the heating sector. Moreover, with the turn towards developing 4th generation district heating, the integral role of district heating in fully renewable energy systems is emphasized further. In Norway, on the other hand, district heating continues to play a minor role, much due to the structure of the energy system, which is based on large hydropower resources, and consequently, exhibits a high electrification share in the heating sector.

In this paper, we look at the role of district heating in a future Norwegian energy system with a focus on how district heating could complement hydropower in a way that would make the use of both of these energy sources more efficient. This research focus is motivated in two ways: first, as part of the European electricity system with increasing amounts of fluctuating renewable electricity, Norwegian hydropower will continue to play an important balancing role with economic value to Norway; and second, Norway is turning towards a greater share of electrification, mainly in the transport- and oil sector, which may increase the electricity demand, and thus, reduce the potentially more valuable balancing capability of hydropower. We take point of departure in the following research question: How can district heating play a part in the Norwegian transition towards a 100% renewable energy system?

The simulation tool EnergyPLAN is used to simulate the operation of a highly electrified future Norwegian energy system, based on existing plans to electrify transport and industrial sectors. Based on experiences from other Nordic countries, several future

district heating scenarios are developed, with focus on the implementation of 4th generation district heating.
Preliminary results indicate that an expansion of the district heating share increases the total energy system efficiency and can contribute to a larger integration of fluctuating renewable electricity production in the country to cover the increased electricity demand from other sectors. However, an expansion of the district heating sector faces challenges in terms of policies, organization and knowledge, and these issues will have to be addressed if the 4th generation district heating solutions are to be implemented successfully.

Roberta Roberto has a PhD degree in Energy Engineering and is currently a researcher at ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development). Her main research activities are focused on integrated energy systems and models. She is the coordinator of the Interreg Alpine Space project IMEAS and National task leader of IEA Bioenergy Task 32.

Towards the integration of prosumers in district heating networks

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Keywords: district heating networks; renewable energy sources; distributed generation; energy storage; sector coupling

Conventionally, district heating (DH) networks have been developed with a centralized logic, with large generation units designed to provide space heating to distributed users. Some networks have already evolved to a stage in which multiple generation units are distributed throughout the network and are supplying heat from different sources and with different schedules.
Some typical concepts of the smart grids could be potentially extended to integrated energy networks, which are characterized by the presence of multiple energy carriers such as electricity and heat. In such a context, distributed energy storage, demand side management and distributed sector coupling could enhance the role of thermal prosumers in DH networks. The potential of ICT technologies in fostering a live optimization of the network, which can be implemented by minimizing energy supply cost for the users or maximizing the exergy efficiency, could lead to new operation logics with very high time resolution.
This paper presents an analysis of the potential effects of opening an existing DH network to the interaction with users. Case studies are based on data from existing DH networks, by simulating an interactive logic in which selected users could participate actively to the network operation, similarly to what occurs in smart grid context through the demand response programs. Distributed heat storage and distributed generation could integrate the capacity installed in centralized generation facilities to allow thermal prosumers to participate to the network operation.
Some technical and economical barriers are discussed, the main being the necessity of lowering the operation temperature of the network to increase the access to some technologies (i.e., heat pumps or solar thermal). The balance of the network needs to be coordinated by a dedicated DH System Operator, with an advanced monitoring capacity on the real heat consumption profile of each user. Moreover, the various

operation strategies adoptable for DH networks based on economic and/or environmental / sustainability aspects are investigated. In addition, the potential benefits of this type of application are evaluated and discussed, with reference to different evolution scenarios for buildings retrofit and RES penetration.

Gunnar Lennermo is a solar thermal consultant in Energianalys AB. Energianalys has designed many solar thermal plants in Sweden as well as some feed-in prosumer installations, especially solar thermal, but also others. Gunnar Lennermo is also a PhD fellow at Mälardalen University.

Requirements for a prosumer facility

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Keywords: prosumers, technical requirements, feed-in substations

A district heating feed-in system is a decentralized heat resource that is fed into the district heating network. There are four different ways to feed-in this heat, return/return, return/supply, supply/supply and supply/return. The most useful is return/supply feed-in but all four of them have their pros and cons.
For about a year, the solar thermal feed-in facility in Ystad is in operation. The Ystad plant is connected both return/return and return/supply. The result so fare is very positive. Some parts can be improved but the solar heat production is high, and the control system works as intended. When the system operates in return/supply mode the feed-in temperature is stable and close to the set point even if the differential pressure, return temperature and solar radiation vary a lot.
Now the next step must be taken for feed-in installations – How should the requirements at the connection point be formulated?
There are some important details that affect the interaction between a feed-in installation and the district heating system.

- Heat-power balance between feed-in facilities and central heat generation
- Fatigue in buried district heating pipes
- A correct feed-in temperature and appropriate temperature range
- Large and/or fast changes in feed-in heat power
- Large and/or fast changes in feed-in flow
- Risk of water hammers (pressure surges)
- Risk of service feed-in pipes freezing
- Handling of the cold plug of water in the feed-in pipes
- Risk of short circuiting at the feed-in substation
- Protection regulations, safety valves, pressure switch and so on

A return/supply feed-in plant gives no risk of fatigue in the district heating pipes if the feed-in temperature is approximately as high as the district heating supply temperature but a large solar thermal return/return feed-in plant that change the return temperature in the main district heating pipes can cause problem. Supply/return may only be used as overheating protection due to risk for fatigue.
Feed-in facilities that can supply heat to two places, return/return+return/supply or secondary+return/supply can relatively quickly change feed-in flow and heat

power from zero to a large number or vice versa, if fast valve actuators are used. Central pumps and central heat generation must be given a chance to handle the change. If the change is too fast, it may even cause a pressure surge in the district heating network. Is it more suitable with a greater temperature deviation from the set point on the feed-in flow in return/supply mode than shift between different operating modes?

The water in the connection pipes from a feed-in plant will cool down if the system has not been operational for a few days, a plug of cold water will be formed. If it is a return/supply feed-in system can this cold plug be pushed into the supply or return pipe. Can the cold plug cause problem in the supply line? If water from the supply line is used to push the cold plug backwards to the return line can this increases the risk of short circuiting in the feed-in substation, is this appropriate?

Susana Paardekooper is doing her PhD in the development of methods and theories for strategic heat planning in smart energy systems. The work described here was done as part of the Heat Roadmap Europe project, which was completed this summer.

The interplay between heat savings and district heating on a national level: an iterative approach

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Keywords: energy efficiency, energy performance of buildings, district heating, energy system analysis, smart energy systems

As heating starts to gain more attention in European decarbonisation strategies, the need for detailed, integrated modelling of the heating and cooling sector within European energy systems increases. Heating and cooling systems in buildings are highly dependent on local conditions, but national and continental energy modelling that simulates the energy demands of the built environment and the operation of an energy system have been scarce. Typically, the focus towards 2050 has either been on increasing the thermal performance of the built environment, electrification, or producing more efficient conversion technologies. A growing body of literature is addressing the need for integrated analysis of the heating and cooling sector together with industry, electricity and transport, at national levels, but often do not consider the (hourly) operation of the energy system, do not include the option of district energy, or otherwise exclude potentials and resources that typify the local nature of heating.

This paper addresses the need for energy efficiency on both the demand side and the supply side. Through iterative energy system simulation and analysis heat demand and the potential for heat savings in the built environment and industry is considered simultaneous to the efficient supply of heat through heat pumps and district heating. By modelling various levels of market penetration for both efficiency measures in building envelopes, heat pumps and district heating, the interplay and trade-offs between these types of efficiency can be understood. This analysis is carried out for the 14 largest countries in EU, and exemplary cases for different issues are chosen and discussed in detail.

The modelling performed builds on the data and methodologies developed in the Heat Roadmap Europe project, meaning that the data regarding the costs and benefits of energy savings, and potential for district energy has been developed on a very granular level. In addition, the results of this approach are novel in that they allow for a better understanding of what the trade-offs and differences are between varying levels of energy efficiency, rather than pointing only towards one optimum.

Overall, the results show that a combination between district heating, heat pumps and efficiency measures in building envelopes leads to the best result. However, the potential for both is bounded and over-implementation of either district heating and of energy saving measures on the demand side can lead to tipping points, after which costs are increased. The most interesting result is the sensitivity between the two; where in some cases, the varying levels of implementation can change the total cost of the heating and cooling sector quite radically, in other cases the difference is much lower. This can contribute towards prioritising the most effective areas for intervention when it comes to stimulating energy efficiency.

The results presented in this paper show the implications of not just implementing energy efficiency on both the demand and supply side of the heating sector, but also the implications of implementing different levels of energy efficiency on both sides of the energy system. This approach not only shows in detail that both are necessary, but also provides a more detailed and nuanced perspective on what the implications would be if we achieve more or less of this efficiency.

Session 19: Smart Energy Systems

Anders N. Andersen is Head of Energy Systems Department at EMD International.

The Danish triple tariff and the radically changing role of CHPs through the transition to a renewable energy system

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Keywords: combined heat and power, thermal store, triple tariff, district energy, support scheme

Combined Heat and Power plants connected to District Energy Plants (DE CHP) have an important role to play in the transition to a renewable energy system, but the role changes radically between the three phases in the transition. In Phase 1 the DE CHP's task is to displace fossil fuelled condensing mode power plants as well as to displace production on individual and communal boilers, thus producing as much electricity as the heat demand allows. In Phase 2, where wind power and photo voltaic (PV) cover a major part of the electricity demand, the DE CHPs participate market-based in the integration of these fluctuating productions and produce less electricity compared to Phase 1. In Phase 3, the DE CHPs are producing even less electricity and are instead providing needed electrical capacity in the few hours, where wind power and PV do not produce sufficient to cover the electricity demand.
This radically changing role of DE CHPs calls for an intelligent and flexible design and operation of these plants. This paper investigates the role of the Danish triple tariff in making these CHPs equipped with large electrical capacity and big thermal stores. It is argued that the Danish triple tariff succeeded making the DE CHPs better adapted to their radically changing role in the transition to a renewable energy system.
The Danish triple tariff is compared with a premium support scheme, and it is shown that for the same total support in a 20-year period the triple tariff promotes larger CHP capacity and much larger thermal energy storage capacity compared to the premium support scheme, furthermore promotes larger displacement of production from condensing mode power plants. However, when coming to Phase 3, the triple tariff must be replaced by a capacity payment to complete CHP's task in Phase 3.

Daniela Guericke is a Postdoc at the Department for Applied Mathematics and Computer Science, Technical University of Denmark. She received her PhD in Business Information Systems from the University of Paderborn, Germany, in 2016. Currently, she is working in the CITIES project focusing on decision-making and optimization under uncertainty in integrated energy systems.

A novel bidding method for combined heat and power units in district heating systems

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Keywords: day-ahead electricity market, combined heat and power, district heating, bidding method operational planning

To optimize the market participation of CHP units in district heating systems is important in today's energy markets, especially with falling prices due to renewable energy sources. The already installed CHP units are getting less competitive in terms of cost, because they are more expensive than heat-only units, which are taking advantage of the low electricity prices (e.g. boilers and heat pumps). Therefore, district heating providers should optimize their offers to the electricity market in order to lower their production costs while providing flexibility to the transmission system operator.

We propose a novel bidding method for the participation of combined heat and power (CHP) units in the day-ahead electricity market. More specifically, we consider a district heating system where CHP units or other heat-only units, e.g., gas or wood chip boilers, can produce heat. Furthermore, the system contains thermal storages to introduce flexibility to the system. We use a mixed-integer linear program to determine the optimal operation of the portfolio of production units and storages connected to the district heating system on a daily basis. Based on the optimal production of subsets of the units, we can derive the bidding prices and amounts of electricity offered by the CHP units for the day-ahead market. The novelty about our approach is that the prices are derived by iteratively replacing the production of heat-only units through CHP production. Due to the limited capacity of the system, the offered production by CHP units is replacing heat production in hours with the highest electricity price forecast in the planning horizon. This results in an algorithm with a robust bidding strategy that does not increase the system costs even if the bids are not won.

We analyse our method on a realistic test case to illustrate our method and compare it with other bidding strategies from literature, which consider CHP units individually. The analysis shows that considering a portfolio of units in a district heating system and determining bids based on replacement of heat production of other units leads to better results.

This work is funded by Innovation Fund Denmark (no. 1035-00027B) through the Centre for IT–Intelligent Energy Systems in cities (CITIES).

Lennart Merkert is holding a Dipl.-Ing. degree in electrical engineering and information technology from Karlsruhe Institute of Technology, Germany. Since 2011, he has been a Scientist at ABB Corporate Research Center in Ladenburg, Germany. His research interests include process control, optimization and energy management in industrial and commercial applications.

Optimal scheduling of combined heat and power generation units using the thermal inertia of the connected district heating grid as energy storage

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Keywords: integrated heat and power dispatch, optimal unit commitment, district heating network, inherent thermal storage, thermal inertia

More and more renewable electricity generators are installed in many countries all over the world. This leads to a more volatile electricity generation and hence to higher and less regular fluctuations on electricity markets. This increased flexibility is posing major challenges for an economic and efficient operation of combined heat and power generation units connected to district heating grids, as they traditionally are operated using a heat drive control strategy. Highly volatile electricity markets with sometimes negative prices can cause big financial losses for the combined heat and power plant operators.

Having a thermal storage can help to avoid these losses and lead to additional financial gains if a smart operations strategy is applied. If no dedicated heat storage tank is installed, the thermal inertia of a district heating gird can be used as a thermal storage as well. However, finding an optimal operation strategy for this inherent heat storage capability is challenging. Supply and return temperatures, mass flow rates and transport times within the district heating grid depend on each other, such that finding an optimal operations schedule is a complex task.

In this paper we propose an optimization-based method using mixed integer linear programming to find such an optimal operations schedule. As several reliable and powerful commercial and open source solvers are available for mixed integer linear programming, it promises a fast roll out to real world applications with acceptable solution times. Such solvers are nowadays used in many industrial applications including the unit commitment and dispatch of power generation units. Nowadays the thermal inertia of a district heating grid is usually not considered in this problem.

Hence, we would like to propose an economically optimal scheduling for combined heating and power plants considering both, electricity markets and heating demand. It allows to consider the inherent thermal storage capability of a district heating grid in the optimization. Two different model formulations for the integration of thermal inertia of district heating grids will be presented. One is based on a close outer

approximation of the storage capabilities of the district heating grid. The other approach is using a linear estimation of the stored thermal energy within the district heating grid based on supply temperature variations. This approach allows a more accurate representation of the thermal inertia of the district heating grid.
Both model formulations will be compared using a small case study showing the savings potential. The savings potential is especially interesting for heating grid operators with longer transportation times. Particularly as no investment in storage tanks is needed and only a change in operations strategy allows to leverage important cost savings.

Sara Månsson is a PhD fellow at the Institution of Energy Sciences at Lund University, Sweden. The focus of her research is to identify and handle issues in district heating systems by combining results from data analytics with knowledge of district heating substations, system operation and buildings.

Faults in district heating substations

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Keywords: district heating substations, experience from industry, fault diagnosis, faults in substations, poor substation performance

District heating (DH) systems of today contain a number of issues that lead to increased system temperatures. One common issue is poorly performing customer substations, which cause decreased cooling of the water in the primary supply system. The poor cooling leads to return temperatures that are higher than theoretically needed, which affects the system performance negatively. The most significant disadvantage of higher return temperatures is that they prevent the district heating distributors from decreasing the supply temperatures of the system. Reduced supply temperatures benefit the system performance in a number of aspects, including less distribution losses, more power generated in CHP plants at the same heat demand, and the possibility to utilize excess heat from industrial sites or a wider variety of renewable sources.

In order to be able to correct the poorly performing substations, it is important to be able to identify what fault is present in the substation. When a fault is present, the behaviour of the substation will change in some way depending on the nature of the fault. By investigating data from the individual substations, it should be possible to identify different faults, depending on the patterns that they create. This identification, or diagnosis, of substation faults, is one of the main focuses of the research project that this paper is a part of. The research project treats an entire fault handling cycle in three steps: fault detection, fault diagnosis, and fault correction. The aim of the fault diagnosis part is to investigate to what extent it is possible to identify faults in customer substations using presently available customer billing data.

The approach taken in the fault diagnosis study is to gather knowledge, information, and experience from the DH industry. This is done in several different steps; the first being a literature study that aims to provide an overview of how far the present research has proceeded in describing and handling faults in DH substations. This is followed by an interview study with DH experts and service technicians at DH utilities. The purpose of the interview study is to take part of experiences and knowledge of common substation faults and how these are identified and corrected. The interview study is followed by a data analysis study, where real and simulated customer data containing known faults is investigated. The aim is to identify if it is possible to detect the faults in the customer data, and, if so, determine the data patterns that occur due to the individual faults. The final step is to implement automatic fault diagnosis methods that can detect the fault patterns identified in the previous step, in unseen customer data.

This paper presents the results of the first parts of the fault diagnosis study, i.e., the literature and interview study. The results describe the experiences of faults in the DH industry, as well as the most common faults present in the DH systems of today.

Session 20: Future district heating production and systems

Carsten Pedersen has worked in Business Development in Grundfos since 2010, strongly focusing on energy optimization and sustainable solutions. Since 2016, he has been responsible for the global District Energy Strategy and earlier, he has focused on energy efficient solutions for commercial buildings.

Reduce heat losses with low temperature zoning

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District Heating is on the rise, since it is considered the most efficient way of distributing energy in most European cities. It is also considered the best way of utilizing various renewable energy sources and surplus heat from factories, data centres etc.
To effectively utilize more renewables and surplus heat (e.g. data centres combined with heat pumps), the supply temperatures must be lowered in many of existing district heating networks. This is often a challenge, since most district heating networks are designed for supplying the consumers with the highest heat demand (e.g. industries, schools etc.).
To solve this challenge, Grundfos has developed a flexible zoning solution where mixing loops (in pits or cabinets) lower the temperatures in a de-centralized manner, e.g. for newer or renovated residential areas (see figure 1). This solution reduces the heat losses by up to 25% in the specific zone and more renewable sources can be utilized for the zone.

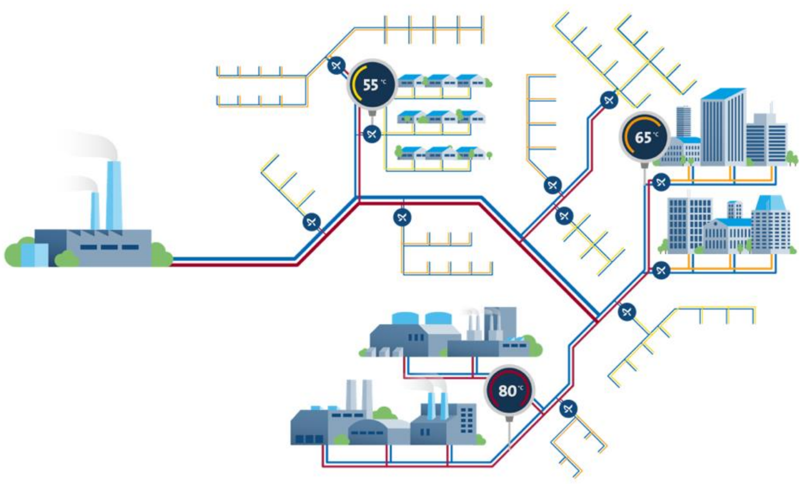

Figure 1: Low temperature zoning

By creating these temperature zones, you can also gain the benefits of distributing your pumps, making it possible to deliver a higher flow and reduce the system pressure.

When lowering the supply temperatures, the differential temperatures will at some point also be reduced, meaning that higher flows are needed ($\Phi = Q * \Delta t$). This can potentially lead to leakage challenges and increased installation bypasses due to the increased pressure in the pipes, which is why we suggest distributing the pumps and operate the system with differential pressures that is just enough to feed the next pumps in the setup (see figure 2). If designed correctly, this de-centralized pumping approach can also reduce the overall system pressures significantly.

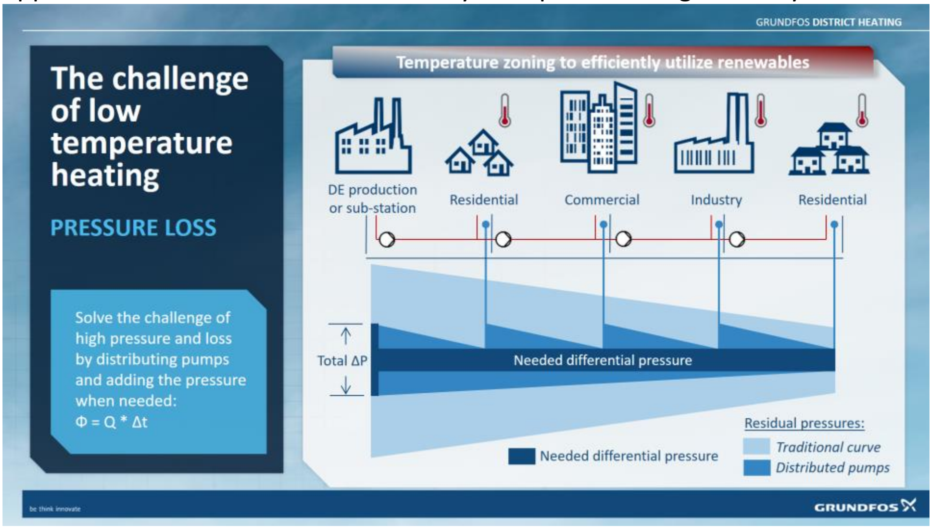

Figure 2: Distributed pumping

Today pressures and temperatures are often exceeding the needs in the critical parts of the system, because it is not measured and operated on real-time basis. So, by installing pressure and temperature sensors with real-time feedback (e.g. in the by-passes), further optimization of the system can be achieved.
All-in-all, this makes it possible to do a controlled decrease of temperatures, which contributes with significant heat loss reductions and the possibility to utilize renewables and surplus heat.

Grundfos is currently establishing field tests in Denmark, Holland and Germany. This is done with Energy-Service that provides intelligent bypasses, pit measure points and the software needed for optimal temperature optimization.

Oliver Martin-Du Pan is a Mechanical Engineer. He completed an industrial doctorate from Loughborough University in 2004 on the operational performance of district heating systems.

A methodology is proposed to reduce heat losses in UK district heating networks and challenging the fourth generation of district heating definition

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Keywords: district heating systems, heat losses

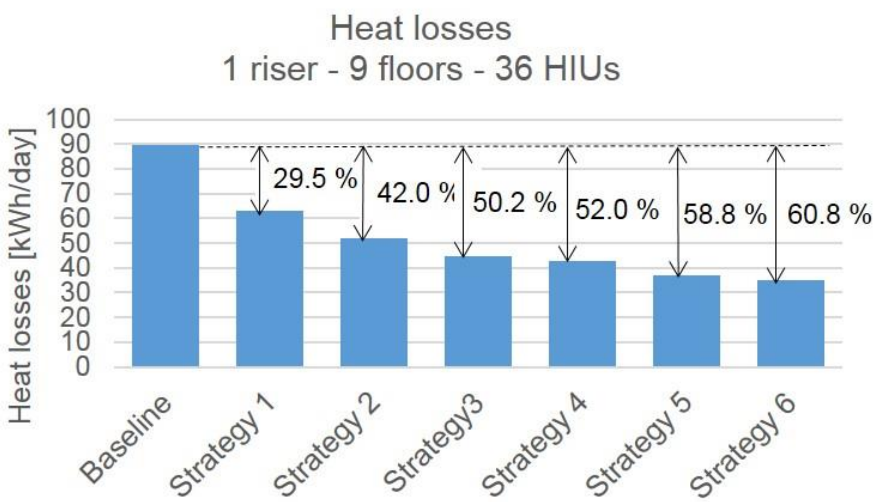
District heating (DH) network heat losses are high in the UK and the Code of Practice addresses this by requiring network return temperatures to be less than 40°C. This study proposes strategies sorted in priority order to reduce networks' heat losses further. This analysis investigates this by assessing and calculating the current heat losses that occur in a typical UK block of dwelling heated at 21°C. As most blocks include several risers, this case study assesses the heat losses occurring from one of its risers to the 36 heat interface units (HIU) connected to it on nine floors. The total length and diameters of the pipes were measured and are showed in the table below.

Pipe diameter (mm)	25	32	40	50	65
Length (m)	108	121.9	6.1	12.3	40.7

Starting from the Baseline, this new methodology to reduce UK heat networks' heat losses suggests to progressively apply the following six strategies in that proposed order when the heat is generated by another technology than heat pumps. These strategies are given here below and the cumulated heat losses reductions are given in the Figure below. Please note that pipes in UK DH networks and as assumed in the Baseline case of this study are usually sized based on having a pressure drop of 250 Pa/m. However, the final pipes connecting each HIU to their laterals are sized at the same size than the adapter fitting incorporated to it. In this case, it was an adapter of 25 mm which was selected to guarantee a peak heating load of 37 kW: Instantaneous HIU supplying heat to one bathroom only. The pipes in the Baseline case are insulated with a phenolic layer of 20 mm and the flow and return temperatures are of 70 and 50°C respectively. 20 mm phenolic layer was assumed because it is not uncommon in the UK to find pipes in blocks to be insulated with an insulation layer of only 17 mm of rockwool and rockwool has a higher thermal conductivity than phenolic.

- Strategy 1: Increasing the phenolic layer from 20 to 40 mm on all pipes
- Strategy 2: Reducing the return temperature from 50 to 40°C
- Strategy 3: Using a new pipe sizing methodology to transport the heat in a 70/40°C DH network (Paper submitted but not yet accepted)

- Strategy 4: To increase the flow temperature from 70 to 90°C at peak times to enable the use of smaller pipe diameters. Peak times were assumed to occur 33% of the time as a maximum percentage. Please note that the electricity consumption and electricity to heat ratio also reduces because less flow is then pumped to the consumers.
- Strategy 5: Removing a plate heat exchanger at the consumer to reduce the flow and return temperature when transporting the heat at peak time from 90°C and 40°C to 85°C and 35°C respectively. When supplying 50% and less of the peak heating load, the flow and return temperature would then be reduced from 70°C and 40°C to 65°C and 35°C respectively. 50% was assumed because to minimise the energy consumed to transport the heat on such a network, it was calculated that the flow temperature must reduce to 70°C when supplying 55% of the peak heating load.
- Strategy 6: Adding a cylinder for the domestic hot water at the consumers (removing the instantaneous DHW units)
- From this analysis, and noticing that the heat can be transported with less energy consumption in a 90/40°C DH network compared to a 70/40°C, shouldn't the definition of the fourth generation of DH be challenged?



Jan Van Deventer is Associate Professor in industrial electronics at Luleå University of Technology.

Interoperability of Smart Energy Systems

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Keywords: cyber physical systems, industrial IoT, system of systems, distributed energy systems, service oriented architecture.

As we continue to evolve towards a sustainable society that maintains a minimum standard of comfort, we proceed to develop smart energy systems or in reality smart energy systems of systems. The obvious example in this context is the 4th Generation District Heating Technologies and Systems (4GDH). Not only are we aiming to reduce the supply temperature within the system, but the sources of heat energy are form a wide variety of origin. They include the byproduct of process industry but also heat byproduct from stores' cooling or refrigeration systems. The sources could be from renewable type such as wind turbines. In other words, many smart energy systems are gradually being developed.

These smart systems have to cooperate together to reach our global goal. Just as an example, a decrease in wind will affect wind turbines and that has to compensated with something else in real time. Collaboration implies communication such that the discussion of interoperability between smart energy systems is just as important as the systems themselves. How do they communicate with each other? What protocol do they use? How do they adapt to changing standards and technologies? Is the communication safe and secure or could someone tamper with it causing system malfunction? Is the concept scalable?

One can leverage the development of cyber physical system within industrial setting into smart energy systems such that we should achieve a harmonious world technically. Industrial IoTs require not only secured and reliable communication but also long-life solution as their product life cycle is extensive. Different Industrial IoT frameworks and platforms are being developed nowadays. We consider one here that promotes this interoperability that is sought. Namely, it is the open source Arrowhead Framework[1],[2]. It is the product of a large EU project that aimed to insure secured and scalable interoperability in an industrial context based on Service Oriented Architecture and the idea of local cloud.

Every instance of a smart energy system could be a local cloud, a self-contained and functional entity, which is composed of sub-systems that interact with each other to provide the desired functionality of the system. One of the advantages of this paradigm

[1] J. Delsing, ed., IoT Automation: Arrowhead Framework. Boca Raton, Florida: CRC Press, 2017.
[2] "Arrowhead Framework Wiki." https://forge.soa4d.org/plugins/ mediawiki/wiki/arrowhead-f/index.php/Arrowhead_Framework_Wiki, 2016. Accessed: 24 May 2018.

is that new sub-systems can be added at runtime due to service-oriented architecture. The local cloud can then in turn offer services to other local clouds or smart energy systems.

To be convincing, we need to move from concept to a reproducible desktop demonstrator in the actual milieu. The demonstrator is a temperature-based flow control. More specifically the flow control of the primary circuit district heating through a heat exchanger via a motorized valve based on the pipe temperature of the hydronic radiators supply. The temperature sensor and the valve are both deemed systems that provide services (e.g., temperature and valve position). A district heating system (a software application) consumes these services for the regulation. What becomes interesting is that that the binding between service providers and consumers is done at runtime allowing new systems to be added later on. For example, adding an outdoor temperature sensor or a diagnosis system, which is what the whole fourth industrial revolution is all about. To ensure security, each system must be authenticated and all communication, which is based on the proven Internet Protocol Suite, is encrypted. This substation demonstrator can then interact with the distribution network or production plant enable a demand response prototype.

Alfred Heller is PhD from the Technical University of Denmark in large-scale solar heating and seasonal thermal storage. After a few years as leader of an IT department in knowledge management, Alfred Heller was appointed Associate Professor in building energy and smart cities at the Technical University of Denmark. Since 2017, he is chief consultant in the field of utilities and district heating at NIRAS consultants in Aalborg, and is responsible for R&D efforts in the supply sectors.

HEATman – Next generation District Heating Concept

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Keywords: district heating, whole system solution, Industry 4.0, digitalization, cloud, IoT, advanced control

Developments are very fast in most technological areas. The district heating sector can draw advantage, if it is able to integrate these very fast changing technologies into the long-term and large-scale infrastructures of the sector. HEATman is a strategic private-public partnership, stewarded by the Danish consulting company NIRAS, moving district heating into the Industry 4.0 area. The main aspects of the project are, to apply digital services across the whole value chain from demand over distribution to production by utilizing cutting edge technologies, implementing state of art research into products and services, adding value for customers. The presentation will line up the partnership, its plans and show examples of future district heating solutions that are monitored, optimized and continuously commissioned across whole systems.
Example applications of the above toolbox are "heat demand modelling" for district heating, Heller, A. (2002) and "automated clustering and labelling of buildings" based on data from e-meters as published by the CITIES project by DTU, Gianniou, P. et.al. (2015) and Gianniou, P. et.al. (2018). These methods are to be implemented in HEATman to classify buildings automatically and aggregate user demands for a given geographical or hydraulic subarea of district heating for a better control and optimization of these.
HEATman provides the necessary, comprehensive infrastructure components, like cloud services and computing services for analysis. Illustrative examples of the infrastructure will be presented. In this early stage, such examples are dominated by research applications, but existing commercially available solutions will be integrated in the holistic and comprehensive solutions platform, HEATman. An idea of the cloud

infrastructure is given by the research setup in Science Cloud for Cities by Liu, X. et.al. (2017) and applied on smart meter data in Iftikhar, N. et.al. (2017).

References:

Heller, A. (2002). Heat-load modelling for large systems. *Applied Energy*, *72*(1), 371-387. DOI: 10.1016/S0306-2619(02)00020-X

Iftikhar, N., Liu, X., Danalachi, S., Nordbjerg, F., & Vollesen, J. (2017). A Scalable Smart Meter Data Generator Using Spark. In *OTM Confederated International Conferences "On the Move to Meaningful Internet Systems"* (pp. 21-36). Springer. (Lecture Notes in Computer Science, Vol. 10573). DOI: 10.1007/978-3-319-69462-7_2

Gianniou, P., Liu, X., Heller, A., Nielsen, P. S., & Rode, C. (2018). Clustering-based analysis for residential district heating data. *Energy Conversion and Management*, *165*, 840-850. DOI: 10.1016/j.enconman.2018.03.015

Gianniou, P., Heller, A., & Rode, C. (2015). Building energy demand aggregation and simulation tools: a Danish case study. In *Proceedings of CISBAT 2015*

Liu, X., Heller, A., & Nielsen, P. S. (2017). CITIESData: a smart city data management framework. *Knowledge and Information Systems*, *53*(3), 699-722. DOI: 10.1007/s10115-017-1051-3

Souman Rudra is an Associate Professor at the University of Agder. He holds a PhD from Aalborg University from 2013 and his work is focused on mathematical modelling and analysis of Power Plants and Biofuels.

Future district heating plant integrated with sustainable hydrogen production

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Keywords: district heating, Norwegian waste, gasification, hydrogen.

This study aims to investigate hydrogen yield potential of municipal solid waste in Norway by integrating district heating plant with a gasifier. Nowadays energy storage in the form of electrolytic Hydrogen is a widespread practice for integration of intermittent renewable energy sources in the smart grid environment, utilizing it in the transportation sector and other industrial applications. Similarly, biomass and municipal solid waste (MSW) use to produce hydrogen by thermochemical processes. The characterization of MSW is a critical step in planning, designing, operating or upgrading solid waste management systems. The experimental characterization of Norwegian MSW using statistical waste data performed. The method used for sampling the MSW was economical and straightforward. The data from characterization used for a theoretical investigation of hydrogen production by gasification of MSW, and water-gas-shift reaction. Three setups were modelled for direct and indirect gasification processes using gasification agent of air, steam, and air-steam. The process models simulated using Aspen plus process simulation software to predict the hydrogen yield potential and heat production from MSW. Besides, a sensitivity analysis conducted to study the effect of operating parameters of gasification and water-gas-shift reactors on the composition of the output of the two reactors.

The result from characterization showed a reasonable agreement with the existing study in the characterization of MSW in different countries. The maximum achieved hydrogen yield from tested setups was around 222g H_2/kg of dry ash-free MSW, which is 94% of the maximum theoretical hydrogen yield from specified MSW. At specific operation condition, the hydrogen and heat produced in steam gasification per one kg of MSW were 199.6 g of hydrogen, and the excess thermal energy heats 4 liters of water to 100 ^{o}C. The indirect gasification with steam as gasifying medium showed the highest hydrogen production potential while the direct gasification was the lowest. From the study integrating indirect gasifier in pre-existing MSW-fired plants can play a significant role in recovering energy from MSW in the form of energy carrier hydrogen. This technology can also reduce the capital cost of building new incineration to handle the increasing waste generation. However, if it is necessary to construct a new waste incinerator, from the result found in this study, it is recommended to build a direct gasification system.

Session 21: Energy planning and planning tools

Casey Cole is MD of Guru Systems, a London-based company providing technology and data analytics for improving heat networks. He has 15 years' experience in software and low carbon energy; first as an engineer and later as co-founder of several cleantech businesses. Casey Cole also chairs the board of Heat Trust, the UK's stakeholder-led customer protection scheme for heat networks.

Using machine learning algorithms to radically improve heat network performance

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Keywords: machine learning, real-time diagnosis, load disaggregation, district heating, energy efficiency, heat network optimisation, customer data

Continuous monitoring and optimisation of district heating networks throughout their operational lifespans is essential for ensuring that heat costs are kept low while upholding a high quality of service to customers. Traditional metering approaches, which focus on energy centres and large substations, are unable to do more than confirm that an issue exists; it is often difficult or impossible to isolate the root cause of poor network performance. To isolate and diagnose the causes of poor performance, it is necessary to obtain and make use of high frequency data from endpoints such as individual residences and block-level junctions on the network.

The analysis of high frequency endpoint data poses significant new challenges that demand equally novel solutions. Manual approaches to data analysis using rule-based heuristics are overwhelmed by the extremely high volumes of data produced by customer meters, while the highly correlated nature of the data makes it difficult to separate causes from symptoms.

Guru Systems has applied machine learning based approaches as a solution to these challenges. Contemporary hardware and algorithmic advances now make it practical to apply these statistical learning technologies in the district heating sector. The characteristics of an optimal solution must include the ability to operate near real-time, scale to terabyte-per-day volumes of fine grained endpoint data, and yield interpretable and transparent solutions.

Our research and development has focused on the application of advances in Bayesian statistical learning and probabilistic programming to radically improve the identification and diagnosis of network behaviour. These machine learning approaches produce highly interpretable output which allows reasoning with uncertainty and thus the quantification of confidence in a given analysis, something which is critical when dealing with incomplete or censored data, as well as the common situation where there are multiple plausible explanations. Additionally, these approaches admit natural and mathematically principled ways to integrate expert domain knowledge with the torrential quantities of newly arriving information and data.

In particular, we present a load disaggregation algorithm utilising Bayesian Hidden Markov Models for classifying real-time HIU data into latent and unobserved mechanical states corresponding to domestic hot water usage, space heating, or other modes of demand. Already in use in a production environment, this tool facilitates the easy identification of many common configuration issues with HIUs without requiring intrusive and expensive metering solutions, as well as pinpointing endpoints that strongly influence overall network performance. Building from the availability of high frequency disaggregated load statistics for all endpoints in a network, structured probabilistic models will be introduced for diagnosing poor commissioning of space-heating and domestic hot water, identification of stuck valves or active bypasses, performing network heat loss analysis, and several other common performance issues. Several case studies where these methods have been used in the field to identify critical network commissioning failures and maintenance issues will be presented along with current opportunities for future projects and enhancements.

Asad Ashfaq is a PhD researcher at Nottingham Trent University, UK. In his research, he is looking at improving the efficiency of 4th generation heating networks, with a focus on the optimisation of low temperature district heating systems with distributed energy storages.

Optimisation of low temperature district heating networks using machine learning methods

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Keywords: low temperature district heating, machine learning, heat demand forecast, thermal heat storage

The low temperature district heating networks have proved to be the most reliable and optimum system for integration of ever-increasing renewable energy in our energy system. The optimisation of these heating networks with correct heat demand estimation, low system temperatures and operation of thermal heat storage is a challenge itself. Therefore, we have developed a data driven control optimisation model which predicts the heat demand and regulates feed-in temperature from the ground source heat pump as well as supply and return temperature in the network. In this study, a small low temperature heating network of 10 homes is considered as case study, where the heat source is ground source heat pump (GSHP) and thermal heat storage. To this end, the heating network is first modelled in Dymola® and supervised machine-learning (ML) techniques have been used to predict energy consumption of the network. The results are then compared with real monitored data of the heating network. The preliminary results from simple control optimisation model show that the Support Vector Regression (SVR) outperforms among other ML algorithms in predicting heat demand and the optimisation of supply temperature especially from stratified thermal heat storage provides significant benefits for energy efficient operation of the heating network.

Russell McKenna is Head of the Group for Renewable Energy and Energy Efficiency at the Chair of Energy Economics, Karlsruhe Institute for Technology (KIT). His research interests focus on decentralised energy systems, especially in buildings and urban areas, for which he develops and employs various energy system models.

Extending a building-scale optimisation model to low-temperature district heating systems

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Keywords: low-temperature district heating, mixed integer linear programming (MILP), decentralised energy systems

Renewable energies are increasingly used for electricity supply, while fossil fuels continue to dominate the heat supply of private households. Renewable energies can be used efficiently for heat supply by means of low temperature heating networks. Many previous contributions have developed and applied energy system models at the building and district scale. Most of these focus on one scale, however, and therefore do not analyse the trade-offs between centralised and decentralised energy supply. This contribution addresses this gap by extending an existing optimisation model from the building scale up to the district scale. It focusses especially on the energy flows between the buildings and the optimal dimensioning of a low-temperature district heating network.

The optimization model further developed in the context of this work minimizes the annualized total expenditures of the individual building energy supply systems, especially the capacities and dispatch of controllable technologies, using a mixed integer linear programming (MILP) approach. The extension to the district level involves the further optimization of the pipe dimensions and the feed pump. In order to enable a combination of decentralised and centralised energy systems and thus reduce model complexity, the location of the heat generation plant and the grid topology are specified exogenously. The energy supply systems employ technologies such as photovoltaic systems, battery storage, CHP, boilers and a low-temperature heat network, and electricity can be imported from the grid. In this paper, an analysis of different centralised and decentralised energy supply systems is carried out on the basis of two urban structurally different residential areas. The systems are compared both in terms of their environmental (e.g. emissions), economic (e.g. costs) and technical (e.g. self-sufficiency) characteristics.

A validation of the newly-developed model with empirical data from an existing district heating network is carried out. The results have a good agreement with this data, including the generation plant and pump sizes. Deviations in the pipe dimensions can be explained by the much higher efficiency of the model network compared to the existing one from the 1970s. This indicates that technological progress could lead to different system designs in modern district heating expansion projects compared to existing ones. Further results for the two examined residential areas show that central energy supply systems are unprofitable for residential areas with a low building and population density due to the high initial investments and the high heat transport losses in relation to demand, as well as higher CO_2 emissions. In contrast, central supply systems can be operated both economically and efficiently for residential districts with a higher building and population density. However, the CO_2 emissions of the centralised and decentralised systems differ only slightly, implying a trade-off between economic and environmental criteria. Further work should focus on analysing different technologies at the district scale, including solar thermal heating and heat pumps. This would enable a deeper understanding the trade-offs associated with centralised compared to decentralised energy supply solutions for different types of neighbourhoods.

Lisa Brange is a PhD fellow at Lund University and her main study field is district heating networks. She has been studying prosumers and their technical and environmental impact on district heating networks and is now studying bottlenecks in district heating networks and how to address these.

Method for addressing bottleneck problems in district heating networks

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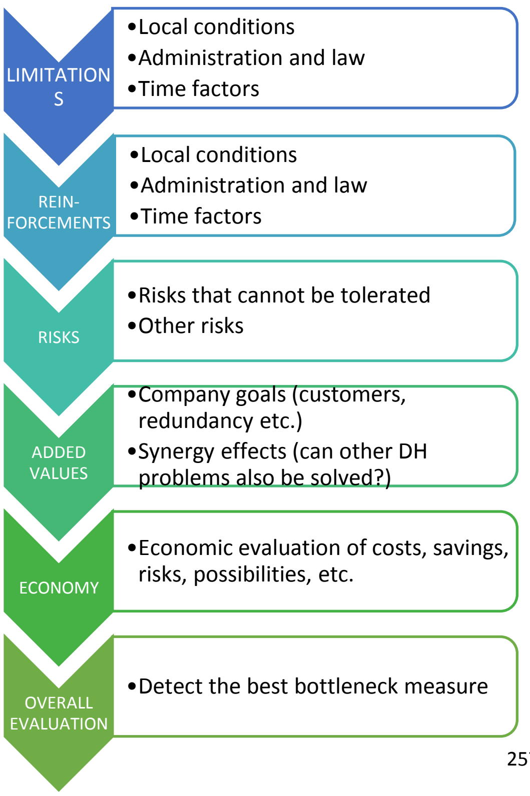
Keywords: district heating network, bottlenecks, 4GDH, optimization

A low supply temperature is an essential feature in the 4th generation district heating (DH) systems. A lower supply temperature is positive for the economy and total efficiency of the DH network as it facilitates renewable and reused energy sources and decreases the heat losses. A lower supply temperature could however be hard to achieve in existing networks, because it leads to a higher flow resulting in higher pressure losses and thus a difficulty in maintaining the differential pressure.
Bottlenecks in DH networks are in this paper defined as when an area does not receive a high enough differential pressure to ensure a sufficient heat delivery. This is often solved by an increase of the supply temperature. But there are also other measures available, such as installing a bigger pipe area, using more pumping, using local heat supply in some form, improvement of the cooling in substations and using demand side management.



This study aims to provide a method for choosing a bottleneck measure when addressing problems with bottlenecks and when optimising DH networks. A lot of the techniques used to address bottlenecks are well-researched and current DH techniques. It is however often not possible to implement all improvement measures at all locations. This work thus provides a method to choose between measures.
This method was developed in three steps. First, a preliminary method was outlined, based on earlier DH bottleneck studies. Thereafter, this method was evaluated in a workshop with the Swedish council for district heating and cooling and by experienced researchers and personnel in the DH field. Lastly, the

method was updated and completed using the collected input. The method developed is general and could be used to evaluate all possible bottleneck measures.
The result is summarised in Figure 1. When addressing a bottleneck measure these steps should be undergone, to detect the bottleneck measure best suited for the local situation. First, limitations are used to eliminate measures not possible to take. In the reinforcement step, some measures are strengthened due to for example local conditions. Thereafter, the risks and added values for the remaining bottleneck measures should be evaluated. The economic evaluation of the measures is the last step before reaching a decision about which measure to use, because all parameters earlier evaluated need to be included in the economy calculation for it to be equitable. In the description of the method, also examples and explanations for the different steps in the bottleneck method are included.

Figure 1. The bottleneck measure method.

The proposed method is thought to be used to help choose between both old and new technologies to optimize DH networks and emphasize more efficient solutions than the most commonly used, in order to eliminate bottlenecks and thus facilitate a lower supply temperature. In doing that, the DH network would become both more environmentally and economically efficient.

Session 22: Low-temperature district heating and buildings

Andra Blumberga is Dr.sc.ing. and Professor at Riga Technical University. She is an expert in modelling system dynamics, in studies of macroeconomics in relation to energy efficiency and renewable energy sources.

Optimisation of energy efficiency measures in historic buildings

Prof. Andra Blumberga (presenter), BSc Ritvars Freimanis, Dr.Sc.Ing. Indra Muižniece, MSc Krišs Spalviņš, Prof. Dagnija Blumberga
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Keywords: smart energy systems, building energy efficiency, internal insulation, historic buildings, bioeconomy, organic insulation materials

Buildings account for 40% of the total primary energy use worldwide. In the new paradigm of energy systems, buildings are part of Smart Energy Systems where they are integrated into electricity, heating and cooling infrastructures. Technology changes in district heating and cooling systems are interconnected with energy consumption in buildings, e.g. reduction of unfeasible investments in building energy efficiency measures, use of excess thermal solar energy, heat recycling or renewable energy sources at a lower cost, more buildings connected to the same district heating network, lower supply temperatures in the district heating network, peak consumption reduction. Although the topic about synergy of energy efficiency in buildings, and district and cooling heating systems is not much studied yet, it promises great opportunities for Smart Energy Systems in future.
International Energy Agency predicts that if no energy efficiency improvements are carried out in the building sector, energy consumption might increase by 50% in 2050. Energy consumption in existing building stock makes up majority of total energy consumed by buildings. Out of that 30-40% is consumed by historic buildings built before the Second World War. Many of them have facades that have historic and cultural value hence only internal insulation of walls can be carried out. This energy efficiency measure is associated with number of risks caused by changes in hygrothermal processes in the massive masonry walls. Due to lower temperatures between wall and insulation material, higher relative humidity levels are reached. The result is frost damage, efflorescence, mould growth, algae growth etc.
Internal insulation can be carried out either with fossil or organic based insulation materials. The Bioeconomy Startegy of EU has set course for a resource-efficient and sustainable economy with the goal to reach more innovative and low-emissions economy by using renewable biological resources from land and sea to produce food, materials and energy. Application of bioeconomy principles to renovation of buildings is very actual. Although the life cycle of organic insulation materials is based on bioeconomy principles, currently they are avoided for internal insulation due to high moisture level which causes mould growth risks.

The main goal of this interdisciplinary research is to find optimal solution for application of innovative organic insulation material made from spruce and pine needles for internal insulation of historic massive walls. To reach the goal, both laboratory tests and simulations were carried out for organic heat insulation made from pine and spruce needles. Tests were carried out with and without application of lime as fungicide to reduce mould growth risk.

Giorgio Cucca is a PhD fellow at the Nottingham Trent University. His actual research field is energy efficiency applied to the building sector, in particular, he is working on deep refurbishment of existing building with the aim to bring them to a near zero energy standard in an economically feasible way, with a special focus on innovative heating systems.

Energy models for deep retrofitted homes using Energiesprong approach

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Keywords: energy system analysis, REMOURBAN, retrofit, heating systems, dynamic simulation, building performance simulation

As part of the EU Horizon 2020 project REMOURBAN a deep retrofitting intervention has been carried out in seven family houses (from a block of 9 terraced houses). The homes have been refurbished to both reduce their energy demand and to implement a renewable energy fed heating system. The refurbishment of the building envelop has been done according to the "Energiesprong" approach. The new energy/heating system comprises a photovoltaic (PV) plant, two ground sourced heat pumps (GSHP), a thermal energy storage (TES) and an electric energy storage (EES). The effects of the deep retrofitting and the performance of the heating system have been evaluated by using two different energy modelling software (Design Builder and IDA ICE). Several different models have been developed using the two software platforms to evaluate the energy performances before and after the refurbishing. The modelling results highlights a substantial reduction in energy consumption, showing also the significant negative effect of the two non-retrofitted dwellings on adjacent apartments and the overall performance of the of 9 terraced houses. It is evident that a potential full refurbishment would have brought to a substantial energy savings. The comparison between the different models shows a substantial congruence between the two software platforms.

Saleh Mohammadi is currently employed as a Postdoc researcher at Delft University of Technology, where he is working on designing integrated energy systems for heating and cooling of the built environment at different scales with a high renewable share. He received his PhD from Eindhoven University of Technology in 2016 in ”Smart Energy Systems”.

Performance analysis of photovoltaic thermal collectors (PV/T) integration with local heat grid configurations, A case study of Dutch renovated house

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Keywords: low temperature district heating, photovoltaic thermal collector, decentralised solar heat supply, simulation

Low Temperature District Heating (LTDH) in combination with (renovated) buildings that can handle heating supply temperatures below 55 °C is a promising system to increase the energy efficiency and foster the energy transition in the built environment. LTDH can contribute significantly in the efficient integration of various local low temperature thermal sources such as solar thermal collectors, (deep) geothermal wells and low temperature waste heat into the heating and cooling system of buildings. Application and integration of solar thermal energy can also play an important role in the energy supply in these systems, usually in combination with seasonal storage, especially when no waste heat or deep geothermal heat is available. Besides, in areas with high energy density, application of decentralized solar thermal systems connected to LTDH can contribute significantly in fulfilling the heat demand of the buildings by renewable sources. One of the emerging technologies which incorporating both heat (PT part) and power (PV part) conversion methods in a single device is photovoltaic thermal collectors (PV/T). PV/T collectors produce heat and power simultaneously and can be integrated readily with new and existing buildings as roof mounted or building integrated system (BIPVT). Usually PV/T collectors are non-insulated and mainly supply heat at temperatures up to 35 °C. In combination with low temperature heat grids (supply approx. 25 °C) the yield of these collectors is even higher. In high-density urban areas, with few local (low temperature) waste heat sources and limited available space for collective heat generation, decentralised PV/T application can provide an important supply of heat to the LTDH. Customers (prosumers), who is connected to the local heat grid, will be able to generate thermal (and power) by their own PV/T system and export the excess to the grid.
In this paper, thermal and electrical efficiency of PVT systems integrated with various configurations of local heat grids (based on temperature levels) are investigated and for each configuration, the simulated thermal and electrical performance will be compared. This study, investigating the effect of LTDH temperature level on the PV/T

efficiency, is a part of the JPI European research project “Smart Urban Isle”. Four distinct configurations based on the configuration of PVT integration and heat grid temperature levels will be investigated. One configuration at the building level, and three grid-connected systems (decentralized feed-in into low temperature heat grid). The grid-connected configurations include integration of PV/T with ultra-low temperature (ULT, approx. 15 °C), low temperature (LT, approx. 25 °C) and medium temperature (MT approx. 35 °C) thermal grids. For the building level configuration, the PVT collectors are not connected to the heat grid and the thermal output is used as a source for the individual heat pump supplying space heating and domestic hot water. For the other three grid connected configurations, the PV/T thermal outputs are also used in the heat pumps in the buildings, while excess heat and power are exported to the heat grid. One of the important quests of this research is exploring the effect of the heat grid temperature level on the thermal and power efficiencies of PV/T collectors as thermal versus electric performance of PVT system has a delicate balance.

Martin Crane is an independent consultant focusing on improving the performance of DH designs and DH in operation. Previous research has looked at substation testing and use of heat meter AMR data for system efficiency improvement. Prior to this Martin Crane worked for a DH utility. Martin Crane is also exploring the scope for community / co-op ownership of DH in the UK.

Low cost domestic retrofit district heating optimisation

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Keywords: return temperature, retrofit, domestic, district heating

In the UK there is little knowledge on the options and costs of connecting of existing domestic properties to a new DH network. Retrofit connections to individual houses has always been assumed to be not cost effective. This research undertakes a number of trials in houses that have recently been connected to a new DH network. Prior to the DH connection the houses were heated with individual oil boilers, the space heating provided by radiators and the domestic hot water provided by a DHW cylinder. The installed systems are open vented and approximately 20 years old and are representative of typical UK heating and DHW installations. A range of minor modifications to the heat exchanger at the point of DH connection, the DHW cylinder and radiators are undertaken and their impact assessed on the reduction in DH return temperatures and the scope to lower DH flow temperatures. The aim of the study is to understand the costs of the improvements and the benefits arsing such that an economic assessment of the each of the installation options can be evaluated. There are cost and practical benefits of reusing as much of the already installed equipment as possible, this work explores the low cost options that will allow more efficient DH network operation, whilst retaining as much of the original heating equipment as possible. Much of the benefit is anticipated through the use of low cost intelligent controls. The monitoring and performance evaluation will rely heavily on customer billing heat meter data collection over m-bus.

Ahmad Said Galadanci is a researcher at Nottingham Trent University. His current research is investigating the effects of thermal bridging in whole building simulation.

Building energy investigation: Understanding our buildings from an energy perspective

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Keywords: thermography, energy modelling, finite element analysis

The Building sector plays a vital role in the consumption of energy amounting to about 20-40% of the total energy consumption in the world. Buildings are designed to be a safe-haven from harsh weather conditions and provide necessary comfort to their occupants. Due to the extreme weather conditions, energy consumption and comfort, it is advised that buildings should be fully insulated. Therefore, care is taken during building design and construction stages to thermally insulate buildings avoiding unwanted heat losses and gains also known as thermal bridges. This is not the case in most of our buildings as there are thermal bridges, which could be avoided. With the Climate Change act in place, buildings are designed to be low energy consuming which are buildings designed to have a minimal energy input to sustain desired indoor temperature. This study aims to investigate and analyse these unwanted heat losses and gains in buildings designed as low energy buildings. A sport changing facility at Clifton Campus, which was designed as a low energy building but not performing as expected was used as a case study. In order to evaluate effects of thermal bridges, an innovative analysis technique that incorporates building thermography and computational analysis using building energy simulation and finite element analysis is used. Results shows that part of the reason why the building is not performing as designed is due to unwanted heat losses and gains within the building envelope. As part of the providing a sustainable building for the present and future, overheating risk assessment of the facility was conducted using energy simulation software and future weather data from the Prometheous project. It was observed that the risk of overheating was high. It was concluded that the unwanted heat gain into the facility contributed to the risk of overheating.

ReUseHeat Session: Urban waste heat recovery - potentials and business challenges

Chair: Alessandro Provaggi DHC+/Euroheat & Power

Urban Persson, Halmstad University: Urban waste heat recovery potential in EU28 - Mapping and geographical visualization

Kenneth Hansen, Aalborg University: Excess heat potential – Urban data in energy system scenarios analysis

Kristina Lygnerud, IVL: Business models and contract arrangements of excess heat

Chris Garside, Nordic Heat: Financing for excess heat

At this seminar, members of the ReUseHeat team will present and discuss the potential of urban waste heat recovery and the business challenges posed by such recovery.

There is enough waste energy produced in the EU to heat the EU's entire building stock; despite of this huge potential, only few small-scale examples of urban waste heat recovery are present across the EU. The objective of ReUseHeat is to demonstrate first of their kind advanced, modular and replicable systems enabling the recovery and reuse of excess heat available at the urban level. ReUseHeat will tackle both technical and non-technical barriers to unlocking urban waste heat recovery projects and investments across Europe. There are four large-scale demonstrators in the project, showing the technical feasibility and economic viability of excess heat recovery and reuse from data centres (Brunswick), sewage collectors (Nice), cooling system of a hospital (Madrid) and underground station (Bucharest). The experience from running the demonstrators and from other examples across the EU will be consolidated into a handbook that will provide guidance for investors and project developers and support future uptake of using urban excess heat. It will include innovative and efficient technologies and solutions, suitable business models and contractual arrangements, estimation of investment risk, bankability and impact of urban excess heat recovery investments and authorisation procedures.

ReUseHeat kicked off in October 2017 and will run for four years. It is funded by the European Union's Horizon 2020 Programme for Research and Innovation.

See more at www.reuseheat.eu

Session 23: Smart Energy Systems

Anders Dyrelund is one of Ramboll's leading energy consultants. His experience is drawn from both the private sector, through consultancy assignments for Ramboll and from the public sector, through the positions he has held in the Danish Energy Agency. He has specialized in least-cost energy planning for sustainable urban development with focus on techno-economic and organisational aspects of district heating and cooling in cities and the interaction with the power system to create virtual electricity storages. In 40 years, he has mainly been involved in the planning, implementation and operation of energy projects in Greater Copenhagen and transfer of this experience to more than 25 other countries.

Cost effective development of a low carbon energy system in cities

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Key words: Low carbon energy, integrated energy system, smart energy, cost-effective, sustainable energy.

How to develop a smart low carbon and cost-effective energy system in cities? The challenge is not to generate renewable energy, but to use it in a cost-effective way, not least because the alternatives to fossil fuels are of low quality, e.g. low temperature heat, or fluctuating electricity from wind and solar energy. It can therefore be a problem to provide our growing cities with clean and environmental friendly energy. However, if we plan them carefully, like a campus owner would do for his own campus, then we can benefit from economy of scale and create cost-effective low carbon energy solutions.

That includes an optimal integration of the 4th generation District heating with the three other energy carriers: electricity, cooling and gas, as well as the building infrastructure.

We have already many examples on how the integrated energy system can be developed in a cost-effective way, e.g.

- Optimal zoning of the DH and DC grids against individual solutions
- Integration of fluctuating wind and solar via DH, DC, electric boilers, heat pumps, CHP and thermal storages, (as if the system was an electric battery)
- Integration of seasonal fluctuations from solar heat via seasonal heat storages
- Active use of thermal resources for combined heating and cooling, e.g. ground water and waste water
- Efficient use of gas as a source for storing bioenergy and electric energy to be used as back-up for heat and power.

Mario Potente Prieto is a chemical and environmental engineer. He is a PhD candidate in the Technical University of Vienna, under the Marie Curie European Project ”CI-NERGY”, linked with Urban planning and energy systems. His contribution is related to the district heating network modelling and optimization, focusing on exergy studies.

Multi-scenario simulation and energy – exergy analysis of a district heating network for a case study in the city of Vienna

<u>Msc Mario Potente Prieto</u> (presenter), Prof. Karl Ponweiser
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Keywords: district heating network, urban energy systems, multi-scenario simulation, heat pumps, heated floors, low temperature systems

On the previous paper [1], the methodology applied for a group of buildings and their district heating network located in the city of Vienna is explained. Operating variables (pressures, temperatures, mass flows) and energy-exergy balances were calculated, in order to fully understand the current network’s performance, predicting vulnerabilities and possible future improvements.
The present article is a further step in which new hypotheses are analysed, defining the future scenarios in which both, network and buildings, might have to work. In each case, other technological options come into play, with the aim of reducing DH water´s temperature, decreasing energy and exergy losses and introducing the use of direct electrical power to feed the network. The final goal will be evolve the actual Viennese system into the 4th generation of district heating networks [4].
The case study remains the same as in the previous article, with the same buildings and local thermal network, though introducing modifications for each exposed scenario. Same software and workflow methodology are used as well. Eight scenarios are defined, based on the following assumptions:

- Actual situation
- Replacement of current heating systems (from radiators to heated floors), with the corresponding buildings´ refurbishment.
- Reduction of system´s temperature, considering Low Temperature District Heating (LTDHN) knowledge [2].
- Introduction of heat pumps in combination with district heating networks, allowing a higher use of electricity in the system [3].

Analysing these balances allows the observation of several behaviours; A decrease of network´s energy and exergy losses is observed for all those scenarios that establish a reduction of feed temperature, producing an increase of 1.33% in energy efficiency. Furthermore, this situation leads to a 2.27% increase of the exergy yield. However, these improvements bring the introduction of heat pumps as a counterpart to support heating or hot water branches integrated within buildings' facilities. There is a high electrical power to be supplied to the heat pumps in order to produce domestic hot water (Scenario 3 = 7.36 W / m^2) or support the heating system (scenario 5 = 7.21 W / m^2), respectively.

An extension of this project is possible, in order to increase computation speed and improve the process of orchestration between the different software involved. In addition, there are other hypotheses that could be simulated, such as the introduction of renewable energies in combination with the district heating network

[1] M. Potente, K. Ponweiser "Simulation and energy-exergy analysis of a district heating network for a case study in the city of Vienna" (In process, not submitted yet)

[2] E. Zvingilaite, T. Ommen and B. Elmegaard and M.L. Franck, "Low temperature district heating consumer unit with micro heat pump for domestic hot water preparation", Proceedings of the 13th International Symposium on district heating and cooling, Copenhage, 2012.

[3] M. Kofinger, D. Basciotti, R.R. Schmidt, E. Meissner, C. Doczekal, A. Giovannini "Low temperature district heating in Austria: Energetic, ecologic and economic comparison of four case studies", Energy 110, 95-104, 2016.

[4] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, "4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems", Energy 68, 1-11 (2014)

Patryk Chaja has used his experience within IMP-PAN in the field of developing software for ship propeller design to create a new programme for the design and analysis of axial turbines. His work has focused specifically on the calculation of the geometry of turbine blades, and verifying results obtained using experimental and numerical analysis. He also conducted a series of experimental studies using a flow tunnel to determine the hydrodynamic characteristics of axial turbines.

Simulation of an alternative energy system for district heating company in the light of changes in regulations of the emission of harmful substances into the atmosphere

Patryk Chaja[1] *(presenter), Maciej Widziński*[1]*, MSc, Eng., Anders N. Andersen*[2,3]*, M.Sc. & B. Com, Marta Kierek*[1]*, MSc, Eng.*
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Keywords: district heating, energy systems analyses, energyPRO, climate and energy package

At the present time Poland is going through a lot of changes, also from the energy generation and energy law point of view. In the nearest future the polish energy industry, according to the EU 2020 Climate and Energy Package, will have to significantly modernize most of its power plants. Dynamically changing situation results in higher demand for different, both energy and economy, analyses helping with setting the frames for future functioning of power engineering companies.
One of the polish power companies, PEC Legionowo, is reshaping its infrastructure to meet the new requirements and from this particular company authors are using data for test case.
The first conceptual work related to the development of the PEC Legionowo energy system is underway in terms of increasing its energy efficiency and reducing harmful exhaust emissions. Due to the need of significantly reducing exhaust emissions by 2022, PEC Legionowo is seriously considering the reduction of the heat generative power from coal-fired boilers. Among others, the resulting energy gap is planned to be covered by installing high-efficiency combined heat and power (CHP) systems. This kind of solution would also eliminate situations when boilers require start-up after a period of withdrawal, when their efficiency is low and exhaust emissions exceed the permissible standards. At the same time, the company does not exclude other possibilities of adapting its energy system to the new law and economic realities. For this combined techno-economic optimization, a modelling software of energyPRO is used.
Current economy situation in Poland and diversification of possible combinations significantly increases the need for performing many various types of detailed energy and economic analyses.

Benedikt Pesendorfer is a PhD fellow at the Austrian Institute of Technology. He received a MSc in Physics from TU Wien and a BSc in Economics from the University of Vienna. His research focuses on topics related to the modelling and simulation of multi-energy systems. Of special interest in this context are the operational aspects of coupling points between district heating and electric distribution networks.

Coupled local district heating and electrical distribution grids: An Austrian case study

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Keywords: district heating, electrical distribution, sector coupling, dynamic modelling, co-simulation

There is significant interest in exploiting hitherto unused synergies by coupling different energy-carrier networks, such as district heating and electrical distribution networks. The transition of these networks from passively coupled to actively linked and operated networks is seen as an important step on the way to smart energy networks. This study addresses the ongoing effort in modelling and simulation of these so-called hybrid thermal-electric networks using tools and semantics that are natural to each of the involved domains, including their controls.
A case study of a residential area in Austria is presented. Multiple buildings, a district heating and an electrical distribution network have been modelled to study the impact of network coupling through different conversion technologies. To this end, the local district heating grid of the case study is modelled in Modelica/Dymola. The district heating network model, thereby, includes the implementation of a main heat supply, a gas-fired boiler, and the grid topology composed of component models for pipes, substations, pumps, etc. Heat demand of the different buildings is modeled as a combination of domestic hot water and space heating demand. The corresponding load profiles were retrieved from synthesized hot water demand profiles and physical building models, respectively. The corresponding electrical distribution grid is modelled in DIgSILENT PowerFactory, a power system simulation and analysis tool. Loads and generation are therein represented by load profiles based on sanitized measured data for the different consumers and for rooftop photovoltaic plants. The models for the electric network and the district heating grid together with controller implementations in Python are coupled via co-simulation based on the Functional Mock-up Interface to enable a detailed technical assessment of such a multi-energy network.
Simulations are conducted for one year for different scenarios with a variation in coupling technologies: heat pumps, electric heaters, combined heat, power units, and their combination with thermal storages. In addition, different control strategies, rule-based and model predictive control, for the operation of the coupling technologies are implemented and compared.

The objective of this study is to assess the impact of distributed coupling of the district heating grid and the electric distribution network with regards to different technologies and control strategies. As well as to demonstrate the use of co-simulation to study such local multi-energy networks and their respective control domains in detail. The main research questions of this study are: (1) What is the impact of balancing the residual electric load on both networks using different coupling technologies (2) How does coupling the electric network and the district heating network affect the greenhouse gas emissions for the different scenarios (3) What are the performance differences between rule-based control and model predictive control.

Alessandro Capretti has a background as Postgraduate Specialized Engineer in Energy Efficiency, Renewable Energy Sources and Distributed Generation. He is in charge of the planning and the design of the district heating network extensions of the systems in Milan, Brescia and Bergamo. Besides, he is in charge of a working group for the development of low temperature DH systems. **Paolo Leoni** is a Chemical Engineer and has been working at AIT in the fields of DHC and Integrated Energy Systems since 2016. Before, he was Project Manager and Engineer for biomass, geothermal, solar thermal power at Enel, where he started working in 2004. His academic education is from the Sant'Anna School of Advanced Studies and the University of Pisa, Italy.

The TEMPO project: Challenges and Opportunities for Implementing Innovative Solutions for lowering the Temperatures in the District Heating Network of Brescia (Italy).

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Keywords: low-temperature district heating networks, innovation solutions, building optimization, dynamic simulations, lowering temperature in existing networks, TEMPO Project

One of the key targets of today's district heating networks (DHN) is to continuously reduce its operational temperatures for increasing the network energy efficiency and environmental performances, enhancing the integration of renewable and residual heat sources and decreasing the operational costs.
The TEMPO project (http://www.tempo-dhc.eu/) addresses these issues by developing and implementing technological solutions in 3 demonstration cases across Europe. Within the duration of the project, innovations related to network digitalisation and building optimization for reducing the DHN return and/or supply temperatures will be implemented, together with innovative business models that can maximise cost savings due to improved energy efficiency to offset the investment costs. The project focusses on three application areas: new low temperature DH networks in urban areas, new low temperature DH networks in rural areas, and existing high temperature networks.
This contribution will briefly introduce the concept of TEMPO and the first results of one innovation developed during the project, regarding the optimization of the building installation. Dynamic building simulations are carried out on different building categories (with respect to size, building physics, usage, heat distribution, refurbishment level) in order to identify and formalized the most common faults that lead to high network return temperatures (e.g. undersized heat-exchanger, leaking substation valve, sluggish heat-exchanger control, etc.). Finally, the status of the existing high temperature district heating network of the city of Brescia in Italy will be

addressed. In this demonstration case, it is planned to implement demand side and supply side measures (digitalization solutions, smart controllers and optimization of the buildings installation), in order to decrease the energy consumption, and enable the transition to lower network temperatures.

Session 24: Future district heating production and systems

Gorm Bruun Andresen is Associate Professor at the Department of Engineering, Aarhus University. Here, he is leading the Renewable Energy & Thermodynamics research group. The research focuses on the domain of applied smart energy and climate change. Of particular interest are the topics of large-scale integration of wind and solar energy, storage and power transmission, next generation district heating, and new smart energy technology. Gorm Bruun Andresen holds a PhD in experimental physics.

Cost sensitivity of optimal sector-coupled district heating production systems

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Keywords: district heating, energy production, optimization, cost sensitivity, fossil free

Goals to reduce carbon emissions and changing electricity prices due to new wind power generation affect the planning and operation of district heating production systems. Through extensive multivariate sensitivity analysis, this study estimates the robustness of future cost- optimal heat production systems under changing electricity prices, fuel cost and investment cost. Optimal production capacities are installed choosing from a range of well-established production and storage technologies. The optimal heat production system is characterized in three different electricity pricing scenarios: Historical, wind power dominated and demand dominated. Coal CHP, large heat pumps and heat storages dominate the optimal system if fossil fuels are allowed. Heat pumps and storages take over if fossil fuels are excluded. The capacity allocation between CHP and heat pumps is highly dependent on cost assumptions in the fossil fuel scenario, but the optimal capacities become much more robust if fossil fuels are not included. System cost becomes less robust in a fossil free scenario. If the electricity pricing is dominated by wind power generation, heat pumps become more favourable compared to cogeneration units. The need for heat storage more than doubles, if fossil fuels are excluded, as the heating system becomes more closely coupled to the electricity system.

Wen Liu is an assistant professor in Copernicus Institute at Utrecht University, the Netherlands. She holds a PhD degree in Energy Planning from Aalborg University, Denmark. Her current research domain is geo-heat technologies and a low carbon built environment.

The marginal pricing mechanism for a competitive wholesale district heating market-a case study in the Netherlands

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Keywords: district heating, marginal pricing mechanism, wholesale market, the Netherlands

District heating (DH) represents a viable way to reduce CO2 emissions associated with heat production. The market model for DH, specifically the introduction of wholesale competition for heat production on DH networks, has been a subject of discussion in North-Western Europe. This study aims to assess if the Marginal Pricing Mechanism (MPM), as applied in liberalized electricity markets, would be an adequate pricing mechanism for a such a market. It does so by addressing the concerns related to the under-recovery of fixed costs for producers when solely relying on the heat market revenues. This will be done by modelling a competitive wholesale DH market including multiple heat production technologies with a linear programming based model for a case study in the Netherlands. The model incorporates supply and demand for heat to obtain an hourly dispatch and heat market prices. Subsequently, the degree to which producers can recover their fixed cost with income from the heat market revenues is assessed.

The results show that only a waste incineration plant can recover its fixed cost with heat market revenues. This suggests additional remuneration is required for the other producers to sustain such a market. The MPM could on the long run enable time-dependent pricing for end users of heat and offer the opportunity for demand side management. However, the results show that the maximum variability in end user prices amounts to 11-24% for the residential sector and 22-48% for the horticulture sector. However, the actual observed price variation over the course of a day is considerably less, which diminishes the potential for demand side management. Nevertheless, it can be argued that given a certain energy mix, the MPM ensures the most cost efficient dispatch by minimizing operational costs. Finally, the analysis provides insight into issues that should be taken into account by policy makers when designing a market model for a competitive DH market.

Maciej Widziński received a MSc in Energy Engineering from the Warsaw University of Technology, Poland, in 2016. He works as research engineer at The Szewalski Institute of Fluid – Flow Machinery PASci on district heating industry simulations including energy and economic analyses. In IMP-PAN, he also uses his experience in the research field of e-mobility, EV charging stations and energy storages.

Comparison in an energy and economic aspects of a real district heating enterprise with a simulation model based on functioning heat and power plant

Maciej Widziński[1] *(presenter), MSc, Eng., Patryk Chaja*[1]*, PhD, Eng., Anders N. Andersen*[2,3]*, M.Sc. & B. Com,*
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Keywords: district heating, energy systems analyses, energyPRO

The use of simulation software is very important in the design and analysis of any power plant. Simulation programs produce different results from one another. Each program also gives different analysis results. This raises the questions of how to construct an effective simulation model within one particular software to be foundation and template for further analyses and if it gives a true view of the situation. In this article authors present power plant of district heating company that has been operating in the city of Legionowo since 1978. Its main responsibilities are production, transmission and distribution of thermal energy. Due to EU Climate and Energy Package, DH Legionowo will have to significantly modernize its technical background meet the new requirements.

The article examines and verifies a simulating model of the existing a heat and power plant and compare the simulations results with genuine data. In the way of comparison there was not only electrical and heat energy considered, but also company's business activity in transactions, investments, financing conditions and investment key figures.

For the modelling of a test case is used the combined techno-economic optimization and analysis software energyPRO. The software optimizes the operation of the modelled system in accordance to all input conditions such as generation and economic data obtained from a functioning heat and power plant in polish industry.

Muhannad Delwati is working as a scientific researcher and PhD candidate at KU Leuven. He works with the H2020 H-DisNet project funded by the European Commission and the aim of his research is to model and simulate a novel thermo-chemical district network based on lab data and case study.

Hasselt case study, preliminary economic aspect and simulation

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Keywords: thermo-chemical district heating/cooling networks; conventional district system; case study; simulation of thermo-chemical processes (absorption/desorption)

The EU 2020 project H-DisNet develops and examines technology for thermo-chemical district networks based on absorption and desorption. To explore the potential of this technology, the case for a district network in Hasselt city in Belgium is studied Fig 1. The contribution will present the estimated amount of residencies and energy consumption in the city area by using GIS data. Based on this data, the amount of thermo-chemical fluid (TCF) required per residency per year is estimated. Moreover, preliminary economic aspects will be presented for thermo-chemical district system against conventional stand-alone heating systems.
The contribution will also introduce some benefits of using H-DisNet district system, such as demand side applications which include space heating/cooling and drying, and regeneration of TCF in DH return flows. Moreover, it will contain a selected simulation results quantifying one benefit or more by using Modelica language Fig 1. To simplify the simulation model due to the high amount of residences in the city area, which are around 40000, representative buildings will be selected in groups based on different criteria. The simulation strategy will be applied to show some benefits of using H-DisNet district system.
The economic study of Hasselt has shown that a H-DisNet network has the potential for competitive performance, both from consumer and operator perspectives, in comparison with conventional heating technologies such as local boilers and stand-alone heat pumps. In a scenario where residential heat demand is met by TCF network as a baseload technology and heat pumps as a peaking technology, economic advantage was seen as slightly lower annualized total costs, all the while providing significant environmental advantage and primary energy consumption savings. Such a scenario – imitating a future smart grid with complementary technologies – can be realized under certain conditions.

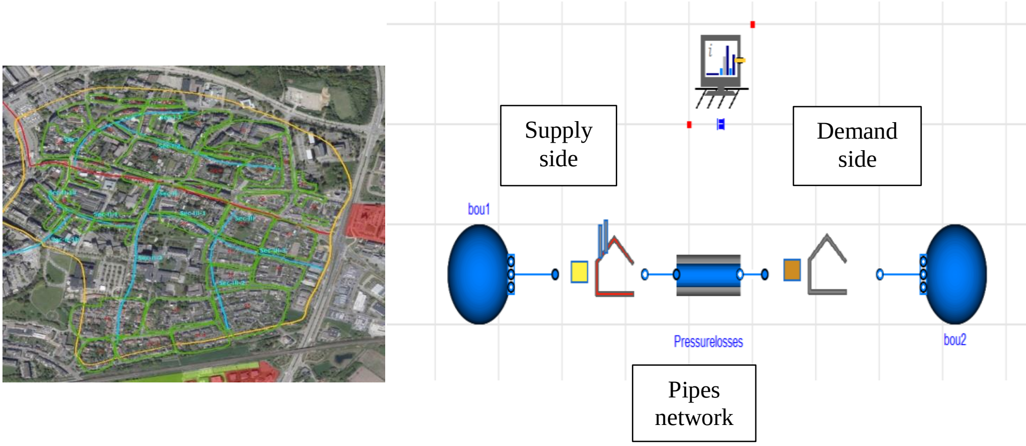

Fig 1: Left, District of Hasselt (Belgium) with network sketch. Right, Dymola scheme model

Kun Zhu is a PhD fellow from the Sustainable Energy System group at Aarhus University. The PhD study is part of the RE-Invest project and Kun Zhu does renewable energy system modelling for Europe, including integrating EnergyPLAN and power flow, and simulating sector coupling by PyPSA.

Impact of CO_2 prices in the decarbonization of coupled electricity and heating sectors

Kun Zhu[1] *(presenter), Marta Victoria*[1]*, Tom Brown*[2]*, Gorm Bruun Andresen*[1]*, Martin Greiner*[1]
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Keywords: sector coupling, energy system modelling, heating sector, grid integration of renewables, CO_2 price, transmission grid

In order to limit the increase of the global average temperature to 2°C it is mandatory to reduce, drastically and in the short time, anthropogenic CO_2 emissions. The cost reduction of renewable energy sources during the last decade, particularly that of wind and photovoltaics (PV), has paved the way to decarbonize the generation of electricity. However, drastically reducing greenhouse gas emissions in the power system will not be enough to avoid exceeding the 2°C limit but a fast CO_2 reduction in other sectors is also mandatory. We investigate the decarbonization of coupled electricity and heating sectors in Europe with a self-sufficient variable renewable (VRES) distribution, with yearly VRES generation proportional to the yearly total demand, to answer the following questions:

- What is the combined effect of a constrained VRES generation and CO_2 price in the emissions from an electricity-heating coupled system?
- Is increasing the VRES penetration enough to achieve a low-CO_2 efficient system or is it economically more favorable to use available energy in a less efficient way at the expenses of higher emissions?
- What is the required CO_2 price to force the gas out of the system and allow 2°C-compatible supply of electricity and heat demand?

Using a simplified hourly-resolved, one node per country network, the electricity-and-heating energy system in Europe is investigated. The most cost-effective system configuration is determined under variable CO_2 price, VRES penetration, and wind-solar mix. It is shown that in order to reach ambitious CO_2 reduction targets, not only large VRES installed capacities are needed, but also a high CO_2 price to force out the use of gas. To achieve 95% CO_2 reduction compared to 1990 level, a CO_2 price of 500€/t is identified with VRES penetration of 0.8. A further discussion is carried out to identify the target configuration, defined as the cost-optimal system to obtain the 95% CO_2 reduction compared to 1990 level. The benefits of increasing transmission between adjacent countries and coupling electricity and heating sectors have been evaluated. Based on the target configuration, the spatial distribution of system cost and primary energy have been examined. The spatial distribution of costs per country illustrates that most investments go into VRES installation and power to heat technologies. The residential and service heat demand is supplied mostly by heat pumps, while resistive heaters and gas boilers are used to cover demand peaks.

Session 25: Energy planning and planning tools

Urban Persson conducts research with a general interest in the development of tools and methods whereby to assess and plan the future deployment of competitive and energy efficient district heating and cooling systems in a European context. Special interests involve heat and cold demands, assessments of excess heat and renewable heat resource sources, heat distribution investment economics, and spatial data analysis in geographical information systems.

Heat Roadmap Europe: Heat distribution costs

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Keywords: district heating, distribution capital cost, heat demand density, land use, Geographical Information Systems, European Union

This paper presents the second step in the development of a comprehensive distribution capital cost model to assess the suitability for district heating in the European Union (EU28). In the first step, Persson and Werner (2011) introduced the theoretical reformulation of linear heat density and modelled a limited selection of heterogeneous city districts in 83 Northwestern European cities. Here, the modelling is improved by using a larger selection of study objects and by adopting a more homogenous spatial entity of land area. These improvements, performed within the Heat Roadmap Europe project, consist in uniform hectare grid mapping of residential and service sector heat demand densities for the entire EU28, upon which basis specific investment costs for heat distribution networks are assessed in a spatially coherent manner. The paper introduces the concept of suitability for district heating, both physical and economic, and adopts a comprehensive overview perspective regarding key dimensions such as land areas, populations, market shares, and investment volumes. Results indicate that 9% (0.4 Mkm^2) of the total EU28 land use area (4.4 Mkm^2) consists of areas where building heat demands are present. However, due to high concentrations in towns and cities, 48% (5.2 EJ) of the total sectoral heat demand (10.8 EJ) originate from urban areas that constitute less than 0.5% (0.02 Mkm^2) of the total area. Due to this high level of densification, the paper evaluates a setting where district heating is expanded individually for each member state according to the general EU28 investment condition at 50% heat market share. At this degree of saturation, the aggregated annual EU28 district heat market amounts to 5.4 EJ and represents an expansion investment volume, starting from current levels (1.3 EJ), of approximately 270 G€. Given this established presence of high heat demand densities in European metropolitan areas, this second study principally confirms the findings of

the first. The conclusion is that pure heat distribution feasibility concerns, alone, should not deter initiatives to expand district heating in European inner city areas.

Tomislav Novosel is a research assistant at the University of Zagreb. His main area of research includes energy planning with a focus on the integration of district heating and cooling systems in the overall energy system. During his studies he has worked on several EU and nationally funded projects including several IEE, H2020 and INTERREG actions.

Heating demand and supply analysis – Development of an energy atlas

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Keywords: district heating, energy atlas, energy supply and demand analysis, GIS

Due to its high energy demand, the building sector of the European Union presents a crucial issue for the decarbonisation of its energy system. A lot of the potential for this relates to the heating and cooling sector, pushing district energy systems much higher in priority for a lot of national and European strategies and regulation. District heating, alongside the increase of efficiency and potential for the utilization of renewable and excess energy, also provide synergy to the power sector with increased flexibility of the overall system through the use of power to heat technologies. All of the above points to the importance of district heating and the heating sector as a whole. Due to the high upfront investment costs related to such systems, detailed spatial analysis of their economic potential is crucial. Heat demand and potential supply mapping is therefore becoming an essential tool in the analysis of the feasibility of new and the expansion of existing district heating systems. This fact is emphasized even further as more and more advances are made in the utilization of excess and renewable heat sources making the knowledge regarding the spatial distribution of supply and demand even more vital. This research presents the creation of an energy atlas which shows the energy demands, potential supplies as well as various demographic and macroeconomic data useful for energy planning purposes and the analysis of the potential for the utilization of district energy systems based on renewable and excess energy. Croatia has been used as a case study for this purpose.

Michiel Fremouw is a researcher at Delft University of Technology, investigating the spatial quantification of renewable energy, application in energy atlases and the relations with urban transition strategies. He has contributed to, amongst others, the European CELSIUS, City-zen and PLANHEAT projects.

PLANHEAT: mapping LowEx HC sources using public geodata

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Keywords: energy potential mapping, urban energy atlas, LowEx, DHC

Decarbonisation efforts are gaining momentum in Europe and there is renewed focus on Heating and Cooling (HC) which, as the Heat Roadmap Europe shows, provides ample opportunities to reduce CO_2 exhaust, especially in urban environments. For planning authorities however, detailed city level geodata on both demand and supply are still difficult to collect and combine. The required data may not be owned by the city itself, and not every city has the resources to appoint dedicated energy planners.
In order to mitigate this, the H2020 PLANHEAT project is developing an open source HC mapping, planning and simulation toolkit to support these efforts, including not only 'conventional' residual and renewable sources but also low temperature ones, and spatially quantifying their potentials for use in the planning and simulation modules.
Although for some 'unconventional' (or LowEx) HC sources some data will still have to be provided by the user, it is possible to streamline this process by providing guidelines and clear instructions on data acquisition. For others, public geodata was integrated into the mapping module, allowing users to quickly gauge local potentials, and increase resolution later by substituting with more detailed source data.

Miguel Chang is a research assistant at the Sustainable Energy Planning Research Group at Aalborg University and is currently involved in the Heat Roadmap projects.

Heat Roadmap Chile: District heating and cooling in the future Chilean energy system

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Keywords: district heating and cooling, district energy, smart energy systems, heat roadmap, GIS, EnergyPLAN, Chile

The purpose of this study is to identify the potential of district energy solutions in Chile, as compared with other heating and cooling options. A main priority for the Chilean government is to implement solutions that could help mitigate the collateral effects on the environment caused by inefficient combustion technologies used for heating. District energy is seen as a potential solution, which aligns to the country's targets regarding improving urban air quality, ensuring energy efficiency and providing low cost sustainable heating and cooling.

The mapping done will identify the extent to which network solutions (like gas and district heating and cooling) are possible, which areas should be prioritized for district heating and cooling development (high potential areas), and where alternative technologies for heating and cooling will need to be implemented. Each grid cell of the heat map will contain modelled estimated heating and cooling demand, local density of demand, basic geometry of DH and DC supply, available waste heat resources, and potential for renewable energy sources that will be mapped in relation to prospective district heating and cooling areas.

Building on the inputs from the mapping, the EnergyPLAN model will be used to analyse the Chilean energy system, and to develop a business as usual scenario and district heating and cooling alternative scenarios. These scenarios will consider changes in the future electricity, heating, and cooling demands; and will also include cost-efficient levels of energy savings, comparing network solutions, comparing individual heating and cooling solutions, and determining the impact of integrating more renewable electricity in the heating and cooling sectors.

Nis Bertelsen is a research assistant at Aalborg University focusing on the implementation of renewable energy technologies and sector coupling in already established socio-technical energy systems. His work includes the modelling of alternative energy systems to showcase possibilities, as well as policy and regulation analyses of the frameworks in which the technology should be adopted.

Review of historical and current European heat planning frameworks: heat market arrangements

Nis Bertelsen (presenter), Research Assistant; Søren Djørup, Assistant Professor; Kenneth Hansen, PhD Fellow; Brian Vad Mathiesen, Professor
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Keywords: heat planning, heat markets, socio-technical systems

Heating and cooling accounts for 50% of the final energy demand in Europe. Energy efficiency and cost-effective deployment of renewables are measures envisioned to enable a sustainable, efficient and stable energy system. In a smart energy systems context, the heating sector needs to be coupled with the electricity sector to increase energy system flexibility and renewable penetration and several research projects have provided possible roadmaps for the technological infrastructure needed for this sector coupling. Strategic heat planning activities can promote the implementation of necessary technologies and energy efficiency measures. As heating is a local and national issue, several heat planning approaches exist across Europe. Some countries have deployed high amounts of district heating; some have deployed gas networks with gas boilers for heating, while some countries have no apparent heat planning activities. Strategies for transitioning the European heat demand to renewable energy must consider these different local contexts.

A term for these heat sector-planning activities could be *heat market arrangements*. Markets are the arenas where repeated exchanges occur, and these are shaped by multiple socio-technical factors. Available resources, technical infrastructure, heat planning legislation and activities, fuel prices including taxation levels, energy efficiency measures, heat demand levels, public perception of technology, trust and knowledge are all factors that shape and arrange the national heat markets. Heat market arrangements can provide understanding of the frameworks within choices of heating occur and why certain countries develop in different pathways. For example, in the Netherlands, 91% of residential heat demand is supplied by natural gas while 43% of residential heat demand is supplied by district heating in Denmark. Both countries have large natural gas deposits and high heat densities, but the heat market arrangements are different in their technological infrastructure, regulations and legislation, price levels, knowledge and competencies.

By considering the different potentials and barriers of heat market arrangements, this analysis can provide a framework for which strategic heat planning activities that should be carried out in certain types of arrangements. As countries differ in heat market arrangements, so must the strategic measures deployed in order to move towards decarbonized heat sectors. This paper analyses the European heat market arrangements in order to provide knowledge on how the current frameworks provide opportunities and barriers to transitions towards smart energy systems.

Session 26: Future district heating production and systems

Louise Ödlund (former Trygg) is a professor in Energy Systems at Linköping University, Sweden. Her research area concerns sustainable energy systems with a focus on system perspective on energy use and supply, and is performed in close cooperation with different actor as for example energy utilities, industries, property owners, and governments.

District heating measures – Driving forces and implementation

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Keywords: district heating, sustainability, system perspective

To transition society towards sustainability is one of the greatest challenge humanity has faced. At the same time as this challenge is serious and alarming, it holds strategic opportunities for actors as municipalities, companies, industries and regions. If they systematically implement resource efficient measures that leads to reduced emissions of global CO_2, they will not only become more attractive in the gradually sustainability-driven market and also be good examples and inspire others to be proactive regarding sustainability. District heating systems in Sweden have been very vital for increased system efficiency and lower climate impact and they will most likely continue to play a central role in society's switch towards sustainability.

But the demand of district heating is reclining and the competition from other heating actors escalates. The reduce district heating demand can be explained by e.g. the fact that current climate change reduces the heat demand for district heating suppliers and that more energy efficient houses are being built. Besides that, several real estate companies are considering replacing installed district heating and instead investing in their own heat pump solutions. Increased knowledge and cooperation with customers is therefore crucial for the district heating industry, and it is today a strong driving force within the district heating industry to get a deeper and closer cooperation with its customers.

The aim of the study is to analyse what measures that can increase the use of district heating in regional energy systems, and to what extend analysed measures regarding conversion to district heating that have been implemented. Impact on global CO_2 emissions are studied as well as economical energy system cost. A system perspective is used including consequences from three perceptions; the combined energy system, users of district heating and district heating companies.

Britta Kleinertz is a project engineer and research assistant, focusing her work on efficient and innovative energy supply concepts for households and industrial purposes. Britta Kleinertz has a special interest in innovative district heating and cooling concepts including intelligent sector coupling (electricity and heat) and the integration of waste heat.

Heat Dispatch Centre – Symbiosis of different heat generation units to reach cost efficient low emission heat supply

Britta Kleinertz[1] *(presenter), Dr. Götz Brühl*[2]*, Theresa Faber*[1]*, Dr. Serafin von Roon*[1]
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Keywords: district heating, heat generation cascade, variation network temperatures

For the transition of energy supply towards a low-emission system, the efficient provision of heat from waste heat and renewable energies is of main importance. Relevant renewable heating sources include solarthermal, geothermal and biomass energy. Additionally, Power-to-Heat systems, based on renewable electricity such as heat pumps, are expected to become highly relevant in order to reduce emissions. Unfortunately, the usage of these renewable heating sources underlies various limitations regarding availability of resources, achievable temperature levels and seasonality.

In this research possible ways regarding the combination of these different heating sources for an efficient heating supply via a "Heat Dispatch Center" are derived from the main advantages and disadvantages of the different heat supply technologies. Furthermore, possible thermal storage concepts for the integration of the overall combination are contrasted.

In order to determine capacities by generation unit and economic efficiency depending on overall system configuration and generation prioritization, a calculation tool was developed. Exemplary evaluations of the Heat Dispatch Center are executed for an exemplary secondary heating network, where a large share of buildings has to be provided with heat of up to 75 °C in winter. To reduce thermal losses, an intra-year variation in supply temperatures per network line and intra-day variation of network supply temperature in summer are assessed.

Several scenarios for hourly future electricity and fossil fuel prices are taken from the FfE energy system model and different scenarios for the development of the thermal energy demand are applied. These scenarios serve as basis for estimating economic sensitivity.

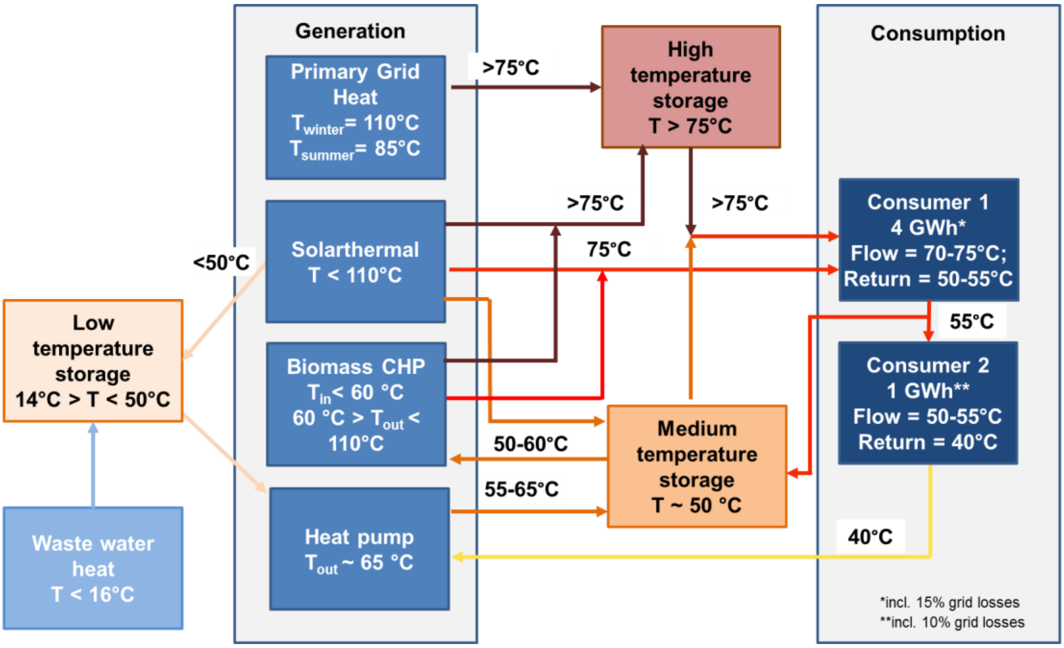

Figure 1: Exemplary interconnection of heat generation and storage units in the Heat Dispatch Center

Toshihiko Nakata is a professor at the Graduate School of Engineering, Tohoku University. He is a Fulbright Scholar at Lawrence Livermore National Laboratory, USA, and a senior researcher at the Central Research Institute of Electric Power Industry, Japan. He also serves on the board of the Reconstruction Promotion Committee of Japan by appointment of the Prime Minister.

Design and analysis of district heating system utilizing excess heat in Japan

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Keywords: district heating, waste heat utilization, heat demand distribution, heat distribution network

The purpose of this study is to identify the effect of installing district heating (DH) utilizing waste heat in Japan. In Japan, final energy use consists of heat (53%), electricity (25%) and fuels for vehicle (27%) and therefore it is necessary to build the environmental-friendly heating system in order to make society sustainable.
Unlike other countries, input energy for Japanese DH consists of 81.5% fossil fuels and recycled heat is responsible for only 15.8% of Japanese DH resource although utilizing wasted heat is historically one of the purposes of installing DH. The structure of DH user in Japan is also deferent from other countries. In almost all European countries, residential sector is the main consumer of DH. By contrast, heat consumption in commercial sector accounts for 98% in Japan. These differences result because, in Japan, the installed place of DH is greatly accumulated in business district in Tokyo. This area is remote from waste heat sources and holds enormous heat demand generated from office buildings.
Thus, designing DH with wasted heat like European system and evaluating its performance are worth analysing in Japan. In this research, we develop the DH utilizing excess heat from waste incineration (WI) and thermal power generation (TPG).
This study's target demands are residential and commercial sector located in 10 prefectures (200,000 km^2) selected on the basis of heating degree days. At first, we calculate heat demand and create load duration curve by 1km×1km mesh in these prefectures. After that heat distribution network between two excess heat resources (WI and TPG) and demand meshes, located within 30km from resources, is designed with GIS (Geographic Information System) and existing road network data, so that LHD (linear heat density) of pipeline between selected mesh and new connected mesh is maximized.
As a result, it is turned out that 47 out of 153 DH systems designed in this research have cost competitiveness against conventional individual heating. These 47 systems have superiorities on CO_2 emission and primary energy efficiency, and they supply 28.6 PJ/year heat in total.

Cord Kaldemeyer is a PhD candidate and research associate. He is an expert in energy system analysis, renewable energies and applied numerical methods.

Integration of varying flow temperatures in unit commitment models of future district heating systems

Cynthia Boysen, M. Eng.; Cord Kaldemeyer, M. Eng. (presenter); Simon Hilpert, M. Eng.; Prof. Dr.-Ing. Ilja Tuschy
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Keywords: sector coupling, district heating, mixed-integer linear programming, temperature

Heat production within fourth generation district heating (4GDH) systems can be realized by district heating (DH) plants consisting of multiple technologies along with storage options. To assess the economic viability and environmental suitability of different setups for respective systems, adequate methods are needed. For this purpose, often mixed-integer linear models solving a unit commitment problem are used. Resulting operation strategies are then evaluated from a technical, economical or environmental perspective to identify suitable technologies, plant setups or energy infrastructure designs.

However, respective models commonly include simplifications to preserve their formal requirements and reduce computational effort. One of these simplifications is the assumption of constant flow temperatures although in practice they vary with heat load, weather conditions and other factors. Furthermore, the overall temperature level in 4GDH networks will be substantially lower than it has been in the past and demands for new technologies. This study investigates how the integration of varying flow temperatures in mixed-integer linear models of district heating systems affects the unit commitment and resulting technology assessment.

To allow for a more detailed representation of different DH supply structures and to represent temperature variations over time, a new model is developed. The system's operational behaviour is depicted using technology specific linearized characteristics based on thermodynamic simulations with varying flow temperatures (Fig. 1). A complete DH plant is then modelled as a combination of various technologies within a generic unit commitment model which optimizes the overall plant revenues by operating at the spot market for electricity while simultaneously serving a defined heat load.

A case study is used to evaluate the impact of integrating temperature variation into the model. For the DH system of Flensburg, an exemplary multi-technology plant design is modelled with three different temperature levels each integrating both a constant and varying flow temperature. Subsequently, the unit commitment (Fig. 2) and resulting overall economic plant performance and emissions are assessed for all scenarios. It can be demonstrated that the consideration of varying temperatures has an impact on the operational results and gains importance with lower temperatures in

4GDH systems. Overall, findings are of importance for both practical future energy system design and scientifically appropriate choices on modelling approaches.

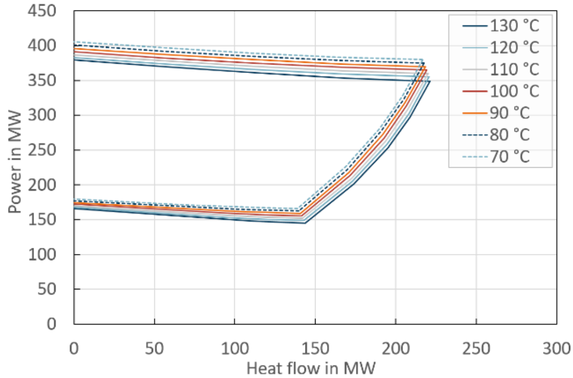

Fig. 2: Operational area of a combined cycle

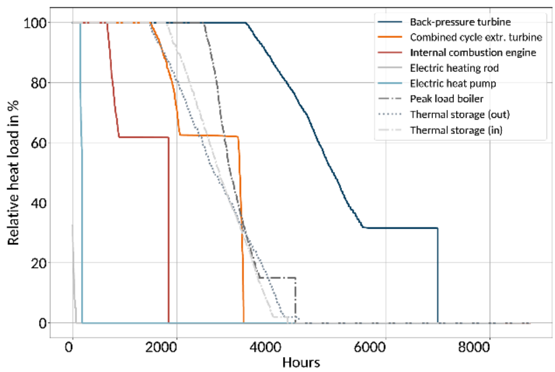

Fig. 2: Exemplary duration curves for DH technologies

Hrvoje Dorotić is a PhD fellow in the energy planning group at the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture. Hrvoje Dorotić's field of work is district heating and cooling, optimization of energy systems and integration of renewable energy sources.

Impact of a waste heat integration on district heating systems' multi-objective optimization results

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Keywords: district heating, multi-objective optimization, energy planning, waste heat, thermal storage

Fourth generation district heating systems are complex due to the large number of possible technologies and energy sources which could be used in order to supply thermal energy to final customers. In addition, these systems are often connected with power sector, natural gas grids and sometimes, even with transport sector through vehicle-to-grid interconnection. In such smart energy systems, waste heat has a crucial role but sometimes its integration could represent challenging task due to seasonality, i.e. mismatch with existing heating demand. Also, temperature difference between heat source and heat sink, i.e. supply temperature of the district heating grid, could be such that booster heat pumps are needed. This paper answers the question: is there a saturation of total cost and total carbon dioxide emissions decrease of the district heating system, with increase of a potentially available waste heat? Such detailed modelling of integration of intermittent renewable energy sources in power sector has already been performed. In order to carry out this analysis, multi-objective optimization was used. Hourly model of district heating system for a whole year horizon was developed as linear programming (LP), i.e. mixed-integer linear programming (MILP). Two objective functions were defined as a total discounted cost, in terms of discounted investment and operational costs which include operational and fuel cost, and total carbon dioxide emissions. In order to handle multi-objective optimization problem, weighted sum approach, in combination with epsilon constraint method has been used. The model is capable of defining supply capacities, including thermal storage size, and hourly system operation for a whole year horizon. The code was written in Julia programming language, while Cbc solver has been used. Available waste heat has been treated as exogenous variable since it is often treated like this in real-life scenarios. Different waste heat hourly distributions with various seasonality characteristics have been analysed. The obtained results show that there is saturation of objective functions once certain share of available waste heat is approached.

Session 27: Smart Energy Systems

Vittorio Verda is a full professor at the Department of Energy Engineering of Politecnico di Torino. Dr Verda received his PhD in Energy Engineering in a dual degree from both the Politecnico di Torino and the University of Zaragoza. Dr Verda is the author of more than 100 scientific papers. His research covers various fields including thermodynamics, heat transfer, thermoeconomics, diagnostic and CFD.

Compact model for the simulation of thermal networks

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Keywords: district heating system, network management, modelling, smart networks, multi-energy-systems, thermo-fluid dynamics model

District heating (DH) is a state-of-the-art technology for providing heat and domestic hot water to the buildings located in densely populated areas in a rational way. Optimal design and management of DH networks require models for simulating the physical behaviour of the network. DH network modelling is crucial to evaluate the response of the systems when design or operating conditions change. Modifications can be planned for increasing the efficiency or flexibility, but they can also be unexpected. Examples of planned modification are storage installation, change in pump operations, rescheduling of the heating systems; unexpected events can be, pipeline leakages and various types of malfunctions.
Models usually rely on the physical description of the fluid-dynamic and thermal problems. These models are usually based on conservation equations applied to all the nodes and the branches of the network. When a) extended networks are considered (several thousands of nodes) b) multiple simulations are required in real-time, c) multi-energy networks are considered, use of physical models can be limiting. In such cases, compact models are preferable.
This work aims at presenting the opportunity to use compact models for simulating thermal transient and fluid dynamic in DH networks. This enables the possibility of simulating network dynamics in a short time. In particular, the compact model proposed preserves the reliability of a physical model because it solves the mass and energy equation. Only the momentum equation is simplified in order to overcome complexity related to the solution of mass and momentum equations, which are coupled.
Results show that the methodology proposed significantly reduces computational costs respect to a traditional physical model. It is suitable for being used in combination with other network models (gas, electricity) and with models of other energy infrastructures, such as plants, storages or energy conversion systems.

Peter Lorenzen has focused on simulations of DHS since the completion of his Master degree and is now doing his PhD. He is also working part-time at the municipal energy supplier Hamburg Energie as a development engineer for new district heating concepts. Since 2017, he is leading the research project “Smart Heat Grid Hamburg“.

Flexibility in district heating systems – a suitable definition and model to describe the temperature and energy flexibility

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Keywords: thermal flexibility definition, thermal flexibility model, temperature flexibility, energy flexibility

Modern district heating systems (DHS) with a higher share of renewable heat sources are classified as 4th generation, which can also include the concept of smart thermal grids (STG). STG are similar to electrical smart grids. There, the fast balancing of demand and generation is key. In contrast, within more inertial DHS low and varying temperatures become additional challenges. At any point in time, not only the amount of energy but also the required temperature must be delivered. STG include different technical concepts utilizing information technology to optimize operation. To calculate and raise efficiency as well as adaptability of DHS, a physical description, taking energy and temperature availability into account, is required.
This physical quantity describing the ability of adaptation is usually called “flexibility”. Even though, the term flexibility is often used, it is not exactly defined for DHS. Because of this, a definition and later physical model was developed. This is backed up by a systematic literature research regarding flexibility in the sectors of thermal, electrical and production systems. The following summarizes their main flexibility characteristics.
On thermal side, DHS construction and operation rely mostly on aggregating mass flow and temperatures to heat (energy) or heat flow as a single quantity. With this, information on heat quality (temperature level) is lost. In cases where exegetic quantities are used, the temperature level is considered, but the information about the ratio of mass flow and temperature is still not transparent.
In the electrical sector energy and power are used for planning purposes as well. But voltage can be transformed to higher or lower levels easily accepting only low losses. Because of this, considering electrical energy quality (e.g. voltage) in the operational planning process is less important than its thermal pendant.
In the field of production engineering flexibilization has started decades ago. In production systems, a variety of processes has to be optimized, that have individual dependencies to each other. Therefore, models and methods have been developed to describe and manage this flexibility. These focus – in contrast to models and methods from the electrical sector – on refining the product characteristics (quality).

Consequently, elementary rules for the management and the treatment of flexibility for production plants and systems have been developed and are used today.
Combining all mentioned approaches lead to a suitable definition of flexibility in DHS. Subsequently, a three-dimensional, discrete physical flexibility model of single DHS components and processes has been developed. With this new flexibility model, variable temperature levels, decentralized generators, flexible customers and more are describable. It can be applied for aggregating (temperature und energetic) flexibility of thermal subsystems, developing and evaluating new constructive hydraulic concepts and planning the operation of complex STG. To demonstrate this model utilization, the flexibility potential of an industrial waste heat plant will be analysed in the paper.
Moreover, it is planned to use this flexibility model for cost optimization. With a higher share of decentralized and renewable generators in DHS, it could be reasonable to use heat markets for the optimization of a large number of plants. The design for such a market should be orientated on physical conditions. The presented flexibility model can be used to aggregate the physical states including the varying heat quality and can be combined with prices to find a useful market design.

Marta Victoria is a postdoctoral researcher at Aarhus University. Her PhD and previous research were devoted to the design, simulation, and characterization of high-efficiency photovoltaic systems. Now, Marta Victoria is focusing on the modelling of large-scale energy systems with high renewable penetration, as well as on modelling PV and wind time series.

Modelling the future contribution of photovoltaics to low-carbon energy systems

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Keywords: energy modelling, reanalysis, time series, solar energy, photovoltaics

In 2016 and 2017, PV was the technology with the highest installed capacity among the renewable energy sources and its cumulative installed capacity reached 390 GW at the end of 2017. With very low capital and operational costs and using a resource widely available, PV is seen as one of the key enabling technologies in the transition towards a low-carbon energy system in almost every country. Recently published works dealing with how to cost-effectively decarbonize the European energy system found that a significant share of generation should be covered with PV. Since most of the energy models use PV generation time series as inputs and PV is expected to play a prominent role, we must ensure that its representation is as accurate as possible to reduce modelling uncertainties.

Long-term hourly time series representing the PV generation in European countries have been obtained and will be soon available under open license. For every country, four different PV configurations have been investigated (rooftop, optimum tilt, tracking, and delta) and are shown to have a strong influence in the daily mismatch curve (electricity demand minus PV generation). To obtain PV time series, irradiance from the Climate Forecast System Reanalysis dataset is converted into electricity generation and aggregated at country level. The Global Renewable Energy Atlas from Aarhus University is used for the conversion and aggregation of PV time series. Prior to conversion, reanalysis irradiance is bias corrected using the satellite-based SARAH dataset and a globally-applicable methodology. Moreover, a novel procedure is proposed to infer the orientation and inclination angles representative for PV panels in a country based on the historical PV output throughout the days around summer and winter solstices.

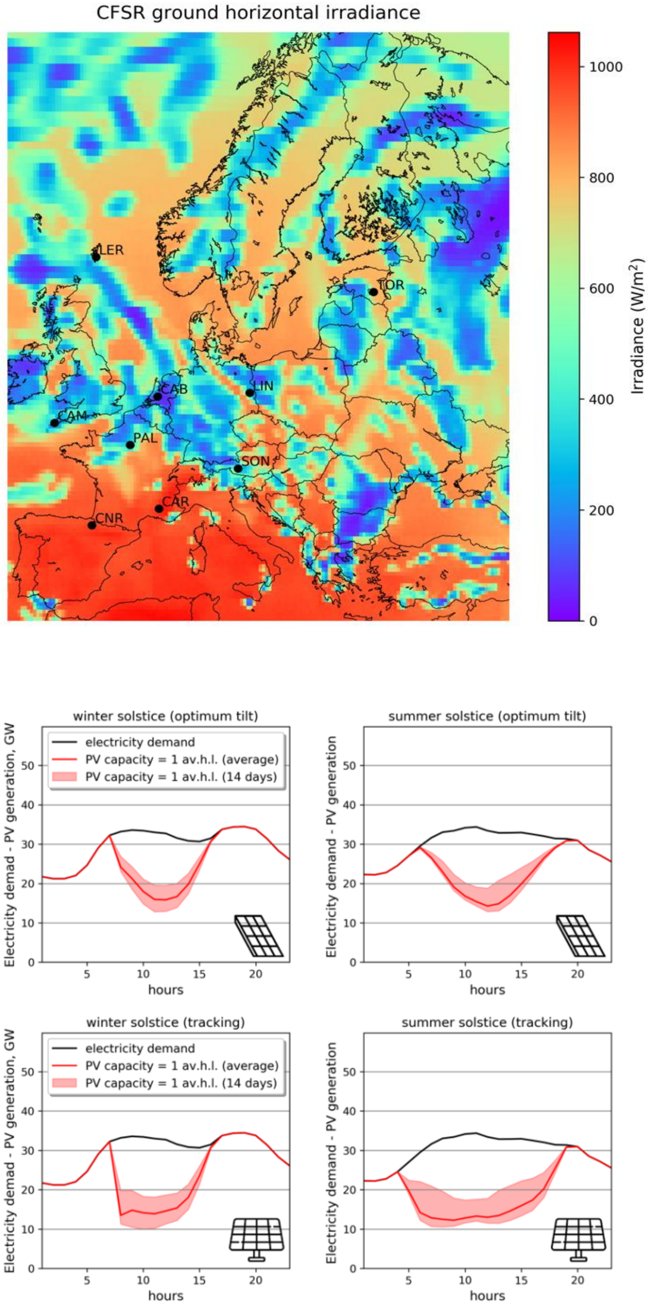


Figure 1. (top) Global Horizontal Irradiance from CFSR reanalysis dataset on the 21st of June, 2015 at 12:00 UTC. (bottom) Electricity demand minus PV generation for winter and summer solstice in Spain, assuming different configurations (optimum tilt and tracking) for the PV panels in the country.

Danica Maljković has a background in power engineering and more than 13 years of experience in the energy sector. Her special interest is in district heating both in the technical and regulatory area, renewable energy with a strong emphasis on geothermal energy sources and marine energy, project development and energy efficiency predominately in industry.

Modelling influential factors of consumption in district heating systems

Danica Maljkovic[1] *(presenter); prof. Igor Balen*[2]*, PhD; prof. Bojana Dalbelo Basic*[3]*, PhD*
[1] *Energy Institute Hrvoje Pozar, Savska cesta 163, 10 000 Zagreb, Croatia, dmaljkovic@eihp.hr*
[2] *University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia*
[3] *University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia*

Keywords: district heating, heat cost allocator, energy efficiency, influential factors, consumption, correlation analysis, two step hierarchical regression analysis.

Assessing the influential factors on measured (or allocated) heat consumption in district heating systems is often limited by the available data. Within a project of modelling consumption in district heating systems using machine learning, an access to a complete billing database of the largest Croatian district heating company was granted. These data comprise of the relevant billing data per each consumer from the period from 2010 till 2017. The company supplies approximately 126,400 final consumers (both households and business) over 375 km of distribution network. The billing database has 40 vectors in a few million single inputs. Additionally, to these data, a questionnaire is distributed to the final consumers in several buildings labelled as “model buildings”, gathering behavioural and demographic data of final consumers (such as occupancy, mode of space usage, heat comfort level, age of occupants, etc.). The two sets of data are then merged and a correlation analysis is performed. Further, two step hierarchical regression analysis is performed based on variables from billing database in the first step, with added behavioural and demographic variables obtained from the questionnaires in the second step. The models from two steps are compared, tested and interpreted. Results of the most influential factors on heat consumption in district heating systems are given and the influence of the behavioural/demographic variables on the prediction accuracy of heating consumption is quantified and interpreted.

Shobhana Singh is an Assistant Professor at the Department of Energy Technology, Aalborg University. She is working in the domain of thermal energy systems. She is actively engaged in various aspects of thermal energy systems such as thermal storage, heating systems, drying systems and their integration with renewable energy. She holds a MSc in Physics and a PhD in solar energy assisted drying systems.

Physical modelling of heat pump for simultaneous space heating and hot water demand

Shobhana Singh (presenter), PhD; Kim Sørensen PhD; Carsten Bojesen PhD; Mads Pagh Nielsen, PhD
Department of Energy Technology, Aalborg University, Pontoppidanstræde 111, 9220 Aalborg, Denmark, ssi@et.aau.dk

Keywords: dynamic modelling, heat pump, Simscape, Two-phase fluid, space heating, hot water storage tank

According to Danish Energy Agency, over 63 % of Danish houses are connected to District Heating (DH) for their heating demand where more than 70 % of DH is generated from combined heat and power (CHP). However, the supply of heat and power to residential as well as commercial buildings is not always accessible. Dense urban areas with high peak demands and complex network of pipes; and newly developed urban areas with uncertain consumption demands pose numerous challenges on DH. Due to larger volumes of water at extremely high pressure, higher peak demands strain DH grid. Moreover, Danish energy system is exposed to strict regulations to have all energy demands in electricity and heating by renewable energy by 2030 and become fossil fuel independent by 2050. Implementation of heat pumps for local heat production mainly in urban areas can reduce the need for expensive DH grid extension and still meet the heat demand. They can also improve flexibility in power supply by utilising the surplus electricity generated by intermittent renewable energy sources for heat production.

This paper aims to access the potential of the heat pump to provide a flexible thermal load at a smaller household level using a physical modelling approach. A dynamic model of an air-to-water, vapour-compression heat pump unit integrated with a hot water storage tank is developed. A 'two-phase fluid' library of MATLAB-Simscape in combination with 'foundation' library is used to simulate the physical components such as such as evaporator, compressor, condenser, expansion valve, house, hot water storage tank and the controller. The modelling framework of the whole system is described and used to analyse simultaneous space heating and hot water demand. An analysis of the system behaviour, based on the consumption profile of a typical residential building in Denmark during the winter season, is presented. The physical modelling in the present work is focused on the requirements to integrate more local heat production units, mainly in dense urban areas, to eliminate the need for new DH pipes. The results show that model satisfactorily depicts the dynamic behaviour of the heat pump with simultaneous heating and hot water demand. In addition, the operation of the heating system is ensured within limits to maintain the indoor thermal comfort. The model is flexible to the changes in the physical input parameters, therefore, will be utilised to investigate performance characteristics of heat pump-based heating systems for local production.

THERMOS National Inspire Event

THERMOS

Steffen Nielsen, Aalborg University: Introduction to THERMOS

Alis Daniela Torres, ICLEI: Transformation from SEAP to SECAP. Overview of THERMOS activities and the sustainable adoption roadmap of the tool

Kamal Kuriyan, Imperial College London: Energy system modelling concepts for district heating

Joshua Thumim, Centre for Sustainable Energy: Introduction and demonstration of the THERMOS tool

User-friendly open-source software to make heat network planning easier

The overall aim of the THERMOS project is to provide the methods, data, and tools to enable more sophisticated thermal energy system planning rapidly and cheaply. THERMOS aims to accelerate the development of new low-carbon heating and cooling systems across Europe, and enable faster upgrade, refurbishment, and expansion of existing systems.

To this end, THERMOS is:

- Developing a state-of-the-art modelling methodology for address-level energy system maps.
- Using this methodology to produce a set of these maps for the pilot cities involved in the project.
- Creating modelling algorithms for analysing these maps in order to support planners with decision making.
- Testing these methodologies in four replication cities.
- Developing and publishing free, open-source software for use by local authorities or other interested parties.

At the moment, the software itself is still under development, but it aims to support planners in accurately, rapidily and cheaply identifying the options for thermal energy networks in any given area. By iteratively designing and developing the methodology and modelling algorithms in partnership with our pilot cities we hope to create software which can produce consistent results - regardless of the geographic scale on which it is applied. We want it to be simple for local authorities to access this information through an easy-to-use application which reflects the detailed models required to underpin local network planning.

THERMOS kicked off in October 2016. A range of experts from universities, local and city-wide authorities, energy and environmental agencies, and specialist consultancies based in the UK, Spain, Poland, Latvia, Denmark, Germany, Portugal, and Romania are taking part in the project. It is funded by the European Union’s Horizon 2020 Programme for Research and Innovation.

See more at www.thermos-project.eu.

Plenary session and panel debate

Plenary Keynote: Transitioning towns, cities, and countries to 100% clean, renewable energy for all purposes

Mark Z. Jacobson, Professor, Stanford University, jacobson@stanford.edu

Keywords: wind, solar, renewables, grids, heating, electricity, roadmaps

Global warming, air pollution, and energy insecurity are three of the most significant problems facing the world today. This talk discusses the development of technical and economic roadmaps to convert the energy infrastructures of buildings, cities, and countries of the world to those powered with 100% wind, water, and sunlight (WWS) for all purposes, namely electricity, transportation, industry, and heating/cooling, after energy efficiency measures have been accounted for. Results showing the ability of the grid to remain stable in each of 20 world regions at low cost under 100% WWS conditions are also discussed. Aside from mitigating global warming, these roadmaps have potential to eliminate 4-7 million air pollution deaths annually, stabilize energy prices, reduce catastrophic risk, and reduce international conflict over energy. Please see http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html for more information.

Plenary Keynote: District heating in China: status quo, challenges and perspective

Xiliang Zhang, Professor and Director of the Institute of Energy, Environment and Economy at Tsinghua University, China, zhang_xl@mail.tsinghua.edu.cn

With the world's largest heat network, China's district heating plays quite an important role in energy consumption and air quality. District heating systems mainly supply space heating in northern urban China belonging to the cold and severe cold climate zones, whose average temperature of the coldest month was under 0°C and HDD18 above 2000.

In 2016, the floor area in the northern urban part was 13.6 billion m^2, accounting for a quarter of the total building floor area, and more than 95% of the floor area used district heating systems, including CHP systems, coal boilers, gas boilers, etc. The energy use intensity of northern urban heating (NUH) was 14.0 kgce/m^2 and total primary energy consumption was 191 Mtce (5.6 EJ), equal to 21% of the energy consumption in the building sector and 4% of the total energy use. Coal was the principle fuel with a proportion higher than 80%. Since 2001, the total energy use increased by more than 1.5 times, while the energy use intensity declined by nearly 40%. How to regulate the energy use and to guarantee the indoor environment is worth studying. Meanwhile, the heating in the northern part is considered as one major source of air pollution emissions and a switch of heat source was promoted in some cities as a result. The relation between district heating and air pollution, as well as the effects of current measures are also worthy of discussion.

Facing these challenges, it is urgent to put forward appropriate approaches to district heating in China. Many options are already available through the use of cleaner and more efficient heat sources; increased efficiency of the entire heating system and decreased heating demand. Key policies or technologies include the use of renewable energy and industrial waste heat, optimum design parameters of the network, promoting the heat reform further, improving building performance, etc. All these above measures are proved to be feasible and cost-effective by real cases. The application of 4th generation district heating in China is also discussed. Based on the status quo, available approaches and development trends, the perspective of China's district heating is given, and the scenario analysis of Beijing's district heating in 2020 and 2030 are taken as a case study. It can be found that with proper planning, it is possible to build an efficient and sustainable district heating system in China, which may contribute to the energy revolution and green development.

Plenary Keynote: District heating and 4th generation district heating in Eastern Europe

Neven Duić, University of Zagreb, neven.duic@fsb.hr

District heating systems are well represented in the Eastern Europe with shares in the final energy consumption for heating close to or more than 50% in Russia, Lithuania, Latvia, Estonia, Belarus and Poland, 40% in Ukraine, Czech Republic and Slovakia and 15-20% in Bulgaria, Romania, Serbia, Hungary, Moldova and Croatia. The other countries are close to or below 10%. Under this condition, there is a huge potential for switching of current district heating systems to next 4th generation of DH systems (4DH) as 4DH may increase security of supply, increase the integration of renewables and waste heat as well as it can bring economic and environmental benefits. However, there are still many barriers that are preventing the development of DH systems. Slowly, the DH networks are being refurbished together with many buildings, but partially refurbished districts still do not allow lowering the temperatures in the whole network so the energy efficiency potential is not utilised to the maximum. There are still many drawbacks in metering of supplied heat as individual measurements are mostly available in the EU countries while other countries still charge their users by common counters usually per square meter of surface. In many countries, inefficient management of DH systems and protectionism of natural gas from the central governments have created a negative picture of DH systems, which is hard to correct. Still there are many positive examples of refurbishment of networks and integration of different type of renewables in the DH system network. Old and inefficient systems mostly powered by fossil fuels call for urgent action and modernization towards the 4DH systems. The presentation will show the results of several initiatives, projects that are planning to improve DH systems in the Eastern Europe, and it will discuss results from different case studies.

Panel debate: The future role of district heating and 100% renewable energy systems

The panel debate will be introduced by Professor Sven Werner, Halmstad University

Sven Werner is Professor of Energy Technology at the School of Business, Engineering and Science, Halmstad University. Sven Werner carries out research about district heating for the future needs in both Sweden and across Europe. His knowledge and research results have been visible in several scientific journals and reports, in textbooks and through numerous lectures. Sven Werner has communicated his research through various activities and presentations in many countries around the world.

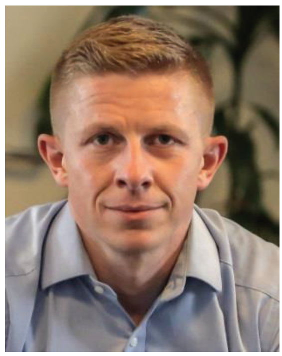
PANEL MEMBERS

Mark Z. Jacobson is Director of the Atmosphere/ Energy Program and Professor of Civil and Environmental Engineering at Stanford University. He is also a Senior Fellow of the Woods Institute for the Environment and of the Precourt Institute for Energy. He received the 2005 AMS Henry G. Houghton Award and the 2013 AGU Ascent Award for his work on black carbon climate impacts and the 2013 Global Green Policy Design Award for developing state and country energy plans. In 2015, he received a Cozzarelli Prize from the Proceedings of the National Academy of Sciences for his work on the grid integration of 100% wind, water and solar energy systems. He has served on an advisory committee to the U.S. Secretary of Energy.

Xiliang Zhang is Professor and Director of the Institute of Energy, Environment and Economy at Tsinghua University and Deputy Director at the Tsinghua-Rio Tinto RES Research Centre. Professor Zhang has been a lead author of the IPCC Climate Change Assessment Reports.

Neven Duić is Professor and Energy Management Chair at the Department of Energy, Power Engineering and Environment, at the University of Zagreb. He has organised a series of conferences on Sustainable Development of Energy, Water and Environment Systems and has been a member of organising, scientific and programming committees of more than 40 research conferences.

Brian Vad Mathiesen, Professor in Energy Planning at Aalborg University, is one of the world's leading researchers in renewable energy systems. He is ranked among the top 1% researchers in the world in the Thomson Reuter's list of highly cited researchers; he is Vice-Chair of the European Commission's Horizon 2020 Advisory Group for Energy (AGE) and is a member of the European Commission's expert group on electricity inter-connection targets in the Energy Union. In his research, Brian Vad Mathiesen focuses on the technological, economic and societal shift to renewable energy, large-scale integration of fluctuating resources (e.g. wind power) and the design of 100% renewable energy systems. Brian Vad Mathiesen was one of the leading researchers behind the concepts of Smart Energy Systems and electrofuels. He has published more than 160 scientific articles and reports and is the editor and editorial board member of various international journals.



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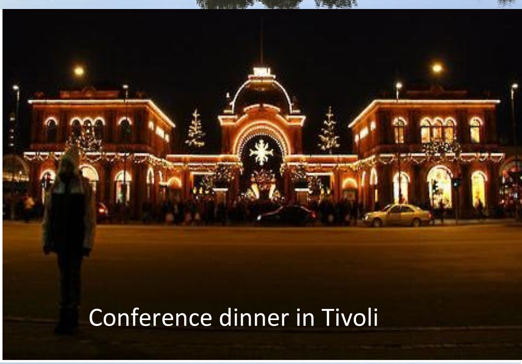

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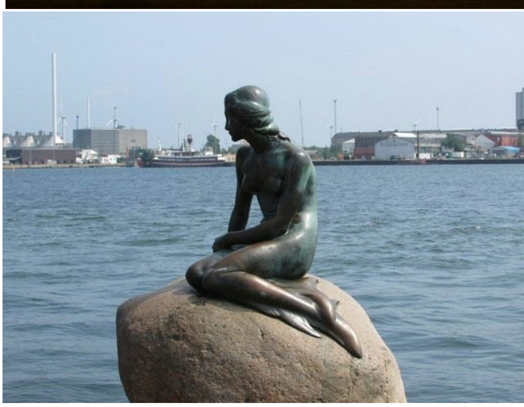

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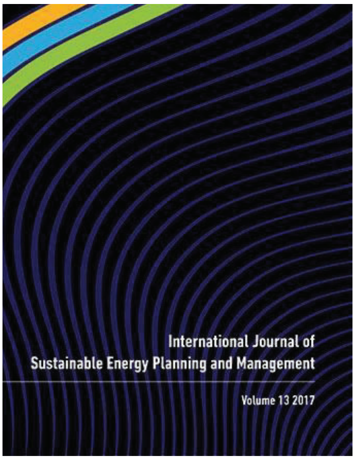

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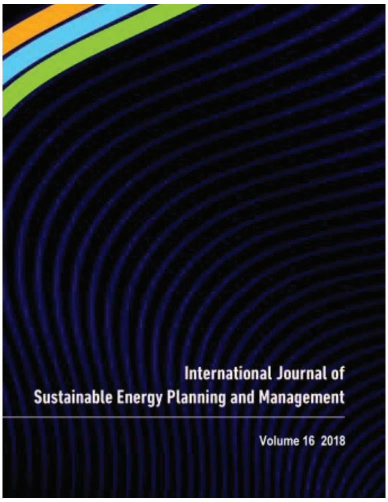

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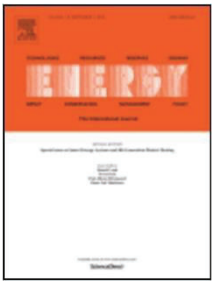

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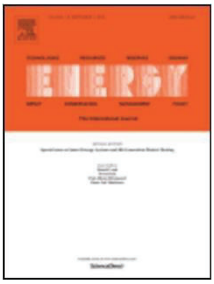

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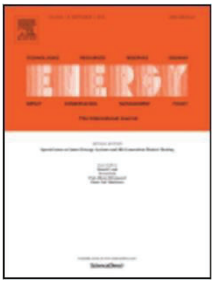

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